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Dynamic Computable General Equilibrium Simulations in Support of Quantitative Foresight Modeling to Inform the CGIAR Research Portfolio

Linking the IMPACT and GLOBE Models

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ABSTRACT

In the context of the project *Quantitative Foresight Modeling to Inform the CGIAR Research Portfolio*, IFPRI's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) was linked to the global dynamic computable general equilibrium model, GLOBE-Energy. This linkage is documented here to provide a detailed account of the methodological approach. GLOBE's role within the analytical framework of the project is to assess the macroeconomic income and welfare effects associated with the alternative pathways for agricultural productivity under the different scenarios and to feed the simulated aggregate income time paths back to IMPACT.

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ABBREVIATIONS AND ACRONYMS

CES	Constant elasticity of substitution
CET	Constant elasticity of transformation
CGE	Computable general equilibrium
CGIAR	Consultative Group on International Agricultural Research
DSSAT	Decision Support System for Agrotechnology Transfer
EV	Equivalent variation
GDP	Gross domestic product
GTAP	Global Trade Analysis Project
HGEM	Hadley Centre Global Environmental Model
IFPRI	International Food Policy Research Institute
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
KLEM	Capital Labor Energy Materials
LES	Linear expenditure system
NoCC	No climate change
R^2	Coefficient of determination
RCP	Representative concentration pathway
SSP	Shared socio-economic pathway

Scenario, region, sector and commodity code descriptions are separately tabulated in main text and Appendix

1. Introduction

In the context of the project *Quantitative Foresight Modeling to Inform the CGIAR Research Portfolio* led by the Internal Food Policy Research Institute (Rosegrant et al., 2017), a linked modeling system centered on IFPRI's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT Version 3 - Robinson et al., 2015) is used to generate long-run projections for the global food system up to 2050 under alternative climate change impact and adaptation scenarios.

One of the components of this model ensemble is the global dynamic computable general equilibrium (CGE) model GLOBE-Energy (Willenbockel, 2015a). Its role within the analytical framework of the project is to assess the macroeconomic income and welfare effects associated with the alternative pathways for agricultural productivity under the different scenarios and to feed the simulated aggregate income time paths back to IMPACT. The linkage of GLOBE and IMPACT serves to endogenize deviations of economic growth from the baseline path.

Rosegrant et al (2017: Appendix D) gives a six-page outline of the methodological approach towards linking GLOBE with IMPACT and presents key results. The purpose of our current background paper is to provide a more detailed account of the methodological approach.

The following section spells out the basic rationale for the approach and explains the methodology. Section 3 provides a non-technical description of the GLOBE-Energy model. Section 4 contains a systematic elaboration of the direct and indirect channels through which agricultural productivity shocks affect aggregate economic performance. To facilitate the exposition, this section uses one climate change scenario (REF_HGEM) as a concrete example. Section 5 presents CGE simulation results for selected key variables across all the scenarios explored in Rosegrant et al (2017) and section 6 provides concluding reflections on limitations and potential directions for the further development of the model linkage approach pursued here. The Appendix contains supplementary technical information including the concordances between IMPACT and GLOBE regions and commodities, and an algebraic description of the GLOBE model.

2. Methodology

2.1. Rationale

In IMPACT, projections for gross domestic product (GDP) growth by country enter the model as exogenous time series and thus remain invariant to agricultural productivity shocks in scenario simulations. The GDP series in IMPACT drive household food demand and as a result serve effectively as a proxy for aggregate disposable household income or aggregate household expenditure. Due to the partial equilibrium nature of IMPACT, feedback effects from productivity changes in agriculture to real GDP and disposable household income are necessarily neglected in stand-alone applications of IMPACT. Ignoring such feedbacks is not particularly problematic for high-income regions where the contribution of agricultural and food processing activities to aggregate GDP is small (Figure 1), but for low-income regions with a large share of agriculture in total GDP the omission of these feedback effects may potentially lead to simulation results that miss an important part of the plot. The linkage of IMPACT with the dynamic CGE model GLOBE serves to address this limitation of partial equilibrium approaches to global food security scenario analysis. The linked modelling framework enables a quantitative analysis of the wider implications of agricultural sector scenario projections generated by IMPACT by taking systematic account of linkages between agriculture and the rest of the economy and allows a theory-grounded general equilibrium analysis of the aggregate income effects triggered by supply-side shocks to agriculture.

2.2. Linking GLOBE and IMPACT

The starting point for applications of the linked GLOBE-IMPACT modelling approach is a dynamic baseline scenario simulation generated by the IMPACT model. The IMPACT baseline paths for exogenous driver variables including GDP growth, population growth and agricultural land supply, as well as the price projections for selected agricultural commodities generated by IMPACT are aggregated to match with the regional and sectoral aggregation structure of the GLOBE-Energy model[1]. These time paths are passed to GLOBE and serve as inputs into the dynamic baseline calibration process for the CGE model.

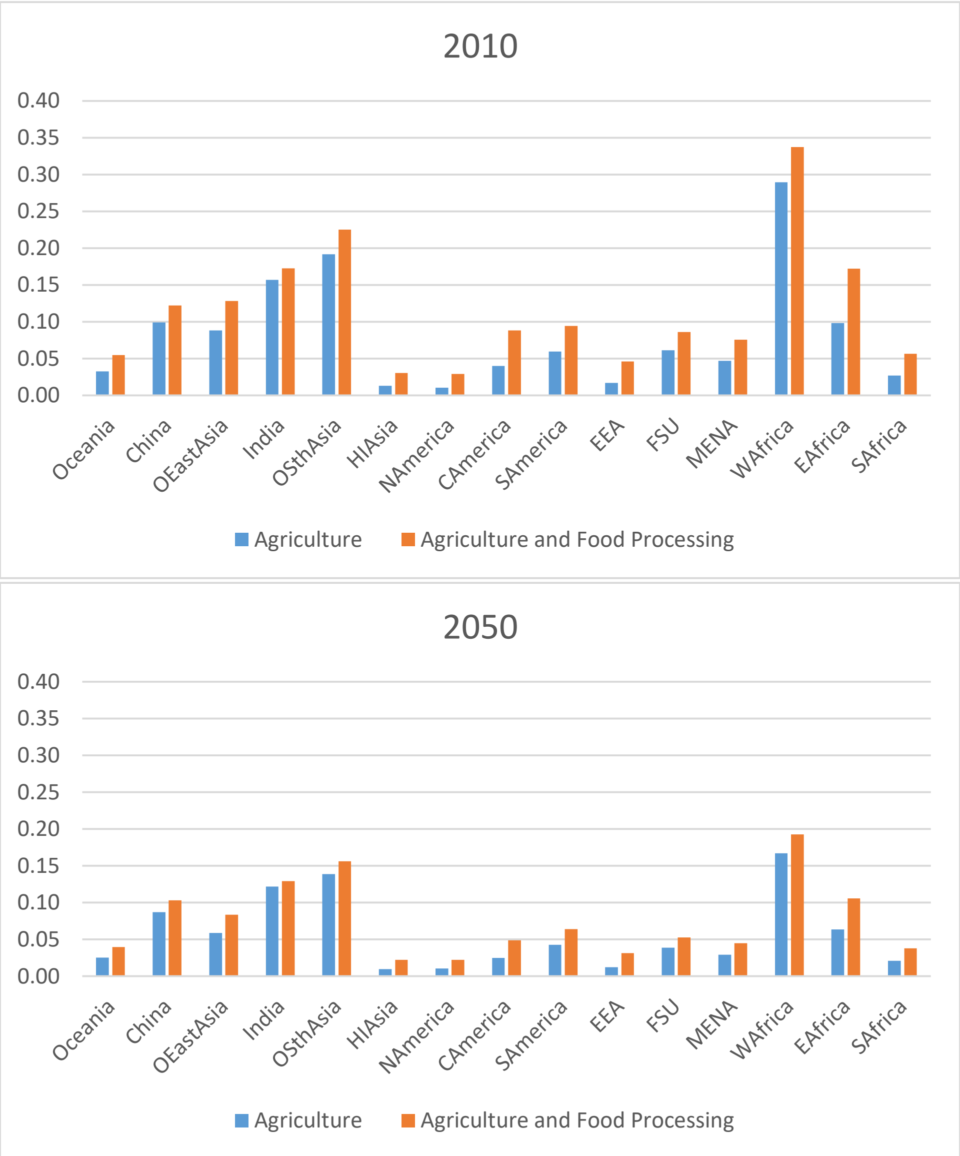
The GLOBE baseline runs are calibrated to exactly replicate the aggregated IMPACT baseline. To assess the economy-wide general equilibrium effects triggered by agricultural supply shocks and to evaluate the resulting aggregate income and welfare effects, the agricultural

[1] See Appendix B for the concordances between GLOBE and IMPACT sectors, commodities and regions.

productivity changes simulated in IMPACT are translated into corresponding productivity changes at the GLOBE region and activity level and are then replicated in GLOBE.

The comparison of the two general equilibrium solutions generated by GLOBE then provides indications of the direction and order of magnitude of the knock-on effects for non-agricultural and macroeconomic variables, such as changes in factor prices and household incomes as well changes in relative commodity prices throughout the global economy. These simulated changes in turn allow an internally consistent assessment of the associated general equilibrium welfare impacts.

Figure 1: Shares of Agriculture and Food Processing in Real GDP 2010 and 2050 - Baseline NoCC Scenario

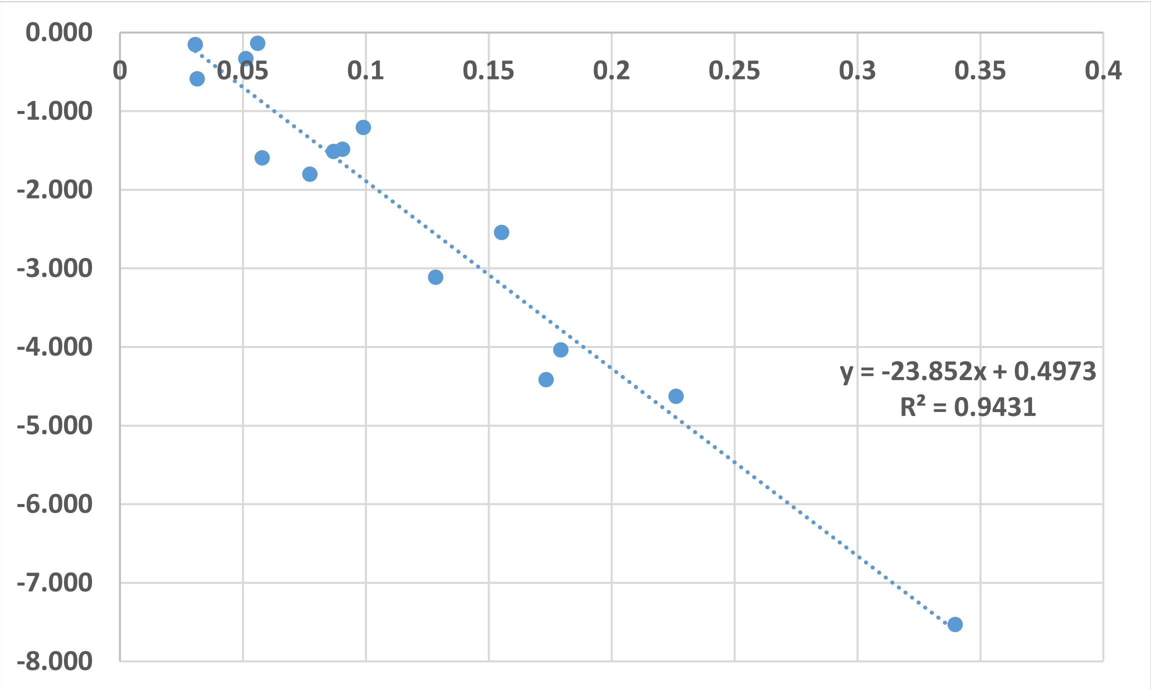


Source: Authors. See Table 2 for a legend to the GLOBE region labels.

The aggregate real income effects associated with the agricultural climate change impact and adaptation investment scenarios generated by GLOBE are then downscaled to the IMPACT regional aggregation level and passed back to IMPACT to analyze the detailed implications for agricultural variables, water and food security.

To downscale the real income effects from aggregate GLOBE regions to IMPACT countries, we exploit the fact that the household real income deviations from the baseline simulated are highly correlated with the initial shares of value added generated by food production (agriculture plus food processing) to GDP – e.g. this ratio explains over 94 percent of the variation in real income effects for Scenario REF_HGEM[2] in 2050 (Figure 2). We calculate the initial food value-added shares in GDP for all 135 regions in the fully disaggregated GTAP 8.1 database and use these figures in regressions to downscale the real income effects to GTAP regions. The results from this step are then rescaled so that the weighted average of GTAP region figures for any composite GLOBE region matches with the simulated GLOBE region results. Finally, the GTAP region results are then mapped to IMPACT regions.

Figure 2: Correlation Real Income Change vs Share of Food Production in GDP – Example REF_HGEM Scenario 2050



Source: Authors

Notes: x-axis – share of food production value added in GDP 2050; y axis – percentage change in household income 2050 in REF_HGEM scenario from REF_NoCC baseline

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[2] REF_HGEM is one of the climate change impact scenarios considered in Rosegrant et al (2017). Results of this scenario are discussed further in section 4 below.

3. The GLOBE-Energy Model

3.1. Overview

GLOBE-Energy is an extended dynamic version of the comparative-static standard GLOBE model originally developed by McDonald, Thierfelder and Robinson (2007). Apart from the incorporation of capital accumulation, population growth, labor force growth and technical progress, the extended model features a stylized representation of the technical substitution possibilities among different energy sources in production using a state-of the-art KLEM (Capital (**K**), **L**abor, **E**nergy, **M**aterials) technology specification.

The model consists of a set of individual country or region blocs that together provide complete coverage of the global economy and that are linked through international trade and capital flows. The modeling system solves the within country models and between country trade relationships simultaneously to ensure full global consistency among all variables – e.g. the sum of all exports across region matches the sum of all imports across regions for each commodity, and global production matches global demand for each commodity.

Each region bloc represents the whole economy of that region at a sectorally disaggregated level. The economic interactions among producers, consumers and the government as well as economic transactions with other regions are explicitly captured. Producers in each region combine primary factors (that is skilled and unskilled labor, physical capital, land and other natural resources) and intermediate inputs obtained from the same and other production sectors at home and abroad to produce output. The output is sold to domestic households, the domestic government, to domestic producers (for use as intermediate input or as an addition to the productive capital stock) and to the rest of the world. The production process generates factor income in the form of wages, other in-kind returns to labor, land and natural resource rents and returns to capital as well as production tax income for the government

The factor income flows to households. Households use their income to pay income taxes, to buy consumer goods and to save for future consumption. The government receives additional tax revenue from sales taxes including revenue from import duties.

The model share parameters governing household, producer and government decisions are set in line with observed data for the reference year 2007, so that the model equilibrium in the absence of policy changes or other exogenous shocks exactly replicates the reference year data.

Producer and consumer responses to price changes are modeled in accordance with microeconomic theory, and the parameters governing the responses to changes in input and output prices are based on the available econometric evidence.

Each region bloc of GLOBE is a multi-sectoral macroeconomic model with microeconomic theoretical foundations. The country models simulate the operation of factor and commodity markets, solving for wages, land and natural resource rents, capital returns and commodity prices that achieve supply-demand balance in all markets. Each region engages in international trade, supplying exports and demanding imports. The model determines world prices that achieve supply-demand balance in all global commodity markets, simulating the operation of world markets.

The model is initially calibrated to the GTAP 8.1 database (Narayanan, Aguiar and McDougall, 2012) that combines detailed bilateral trade, and protection data reflecting economic linkages among regions with individual country input-output data, which account for intersectoral linkages within regions, for the benchmark year 2007. The model version employed in the present study distinguishes 24 commodity groups and production sectors (Table 1) and 15 geographical regions (Table 2).

3.2. Production, Input Demand and Factor Markets

Production relationships by activity are characterized by constant returns to scale and specified by nested Constant Elasticity of Substitution (CES) production functions. In the standard version, activity output is a CES composite of an aggregate intermediate input and aggregate value added, where the aggregate intermediate input is a Leontief aggregate of the individual intermediate commodity inputs and aggregate value added is a CES composite of primary factors. The determination of product supply and input demand is based on the assumption of profit maximizing behavior.

For each region bloc, the model allows to adopt either a standard neoclassical factor market closure or a closure with labor underemployment. Under the former closure, factor markets in all regions are characterized by inelastic factor supplies and the model solves for market-clearing factor prices. The primary factors except sector-specific natural resource endowments are mobile across production activities, but immobile across borders. Under the latter closure option, the wage for unskilled labor is fixed relative to the domestic consumer price index and the supply of unskilled labor is perfectly elastic.

Table 1: GLOBE Sector Aggregation

Short Code	Description	GTAP Sector Code*
Rice	Rice	pdr, pcr
Wheat	Wheat	wht
OCereals	Other Cereals	gro
Oilseeds	Oil Seeds	osd
SugarCane	Sugar Cane and Beet	c_b
OCrops	Other Crops	ocr, pfb
Cattle	Bovine cattle, sheep and goats, horses	ctl
OLvstkPrd	Other Livestock Products	wol, oap, rmk
VegOils	Vegetable Oils and Fats	vol
Sugar	Sugar	sgr
OPrFood	Other Processed Food	cmt, omt, mil, ofd, b_t
Coal	Coal	coa
Oil	Crude Oil	oil
NatGas	Natural Gas	gas, gdt
ONatRes	Other Natural Resources	omn, frs, fsh
LgtManuf	Light Manufacturing	tex, wap, lea, lum, ppp, omf
Petrol	Refined Petrols	p_c
Chemics	Chemicals, Rubber and Platics	Crp
OManuf	Other Manufacturing	nmm, i_s, nfm, fmp, mvh, otn, ele, omc
Electricity	Electricity	ely
Water	Water Distribution	wtr
Constrc	Construction	cns
TrdTrns	Trade and Transport Services	trd, otp, wtp, atp
OServic	Other Services	cmn, ofi, isr, obs, ros, osg, dwe

See Annex Table B4 for the key to the GTAP sector codes

Table 2: Region Aggregation

Short Code	Description
Oceania	Australia, New Zealand and Other Oceania
China	China
OEastAsia	Other East Asia
India	India
OSthAsia	Other South Asia
HIAsia	High-Income Asia
NAmerica	North America
CAmerica	Central America and Caribbean
SAmerica	South America
EEA	European Economic Area
FSU	Former Soviet Union
MENA	Middle East and North Africa
WAfrica	West Africa
EAfrica	East and Central Africa
SAfrica	Southern Africa

3.3. Energy Production and Intermediate Use in the Extended Model

In energy-focused CGE modelling, technology specifications belonging to the generic class of KLEM (Capital (**K**), **L**abor, **E**nergy, **M**aterials) production functions are commonly employed to capture substitution possibilities among energy and-non-energy inputs and among different energy sources.[3] GLOBE-Energy follows this established standard approach. The sectoral KLEM production functions for activities selected by the user take the form of nested multi-level functions with a (positive or zero) constant elasticity of substitution (CES) among inputs grouped together within the same nest. Figure 3 displays the input nesting hierarchy, which replaces the two-level nesting structure of production in the GLOBE standard version described in the previous section for the selected sectors.

In each sector, the production of a given output quantity requires non-energy inputs and a composite value-added/energy composite in fixed or variable proportions. For the few sectors that use crude oil directly as an input (i.e. the refined fuels industry and the chemical industry), crude oil inputs are a fixed proportion of output. The value added/energy composite requires energy and primary factors in variable proportions. Thus, when the price index of energy rises relative to primary factor prices, energy inputs are replaced to some extent by additional inputs of capital and labor. In other words, the model generates a shift towards less energy-intensive modes of production in response to an increase in energy prices. In this framework, a transition towards a higher share of hydro, solar or wind in the power mix in response to higher fossil fuel prices is represented in a stylized form as a substitution of fossil fuel inputs by physical capital.

Required energy inputs are composed of electricity purchases from the electricity sector in the model and direct use of fossil fuels. The model allows substitution of these primary fossil energy carriers for electricity in sectors where the input-output matrices of the GTAP database record intermediate purchases of fossil fuels. At the bottom of the input substitution hierarchy, the sectoral production functions allow for imperfect substitutability between coal, refined oil and natural gas.

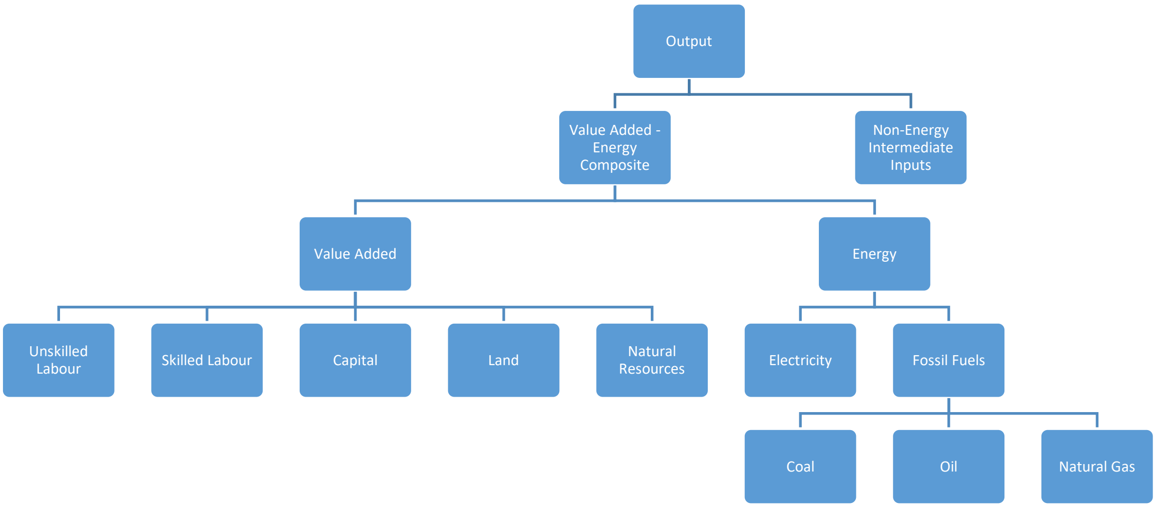
3.4. Final Domestic Demand by Commodity

The commodity composition of government consumption demand and investment demand is fixed using the observed demand patterns from the benchmark data set, while the determination

[3] See Willenbockel (2015a) for references to the related literature.

of the aggregate levels for these final demand components in each region depends on the choice of macro closure, as explained below. Households are utility maximizers who respond to changes in relative prices and disposable incomes. In this version of the model, the utility functions for private households take the Stone-Geary form and hence consumer demand by commodity is described by a Linear Expenditure System (LES) specification.

Figure 3: Production Function Nesting Structure



3.5. International Trade

Domestically produced commodities are assumed to be imperfect substitutes for traded goods. Import demand is modelled via a series of nested constant elasticity of substitution (CES) functions; imported commodities from different source regions to a destination region are assumed to be imperfect substitutes for each other and are aggregated to form composite import commodities that are assumed to be imperfect substitutes for their counterpart domestic commodities The composite imported commodities and their counterpart domestic commodities are then combined to produce composite consumption commodities, which are the commodities demanded by domestic agents as intermediate inputs and final demand (private consumption, government, and investment). Export supply is modelled via a series of nested constant elasticity of transformation (CET) functions; the composite export commodities are assumed to be imperfect substitutes for domestically consumed commodities, while the exported commodities from a source region to different destination regions are assumed to be imperfect substitutes for each other. The composite exported commodities and their counterpart domestic commodities are then combined as composite production commodities. The use of nested CET functions for export supply implies that domestic producers adjust their export supply decisions in response to changes in the relative prices of exports and domestic commodities. This specification is desirable in a global model with a mix of developing and developed countries that produce different kinds of traded goods with the same aggregate commodity classification, and yields more realistic behavior of international prices than models assuming perfect substitution on the export side.

3.6. Macro Closure

Current account balances for all regions are assumed to be fixed at initial benchmark levels in terms of a global numeraire and real exchange rates adjust to maintain external equilibrium. Under the default macro-closure, changes in aggregate absorption are assumed to be shared equally (to maintain the shares from the base data) among private consumption, government, and investment demands. Household and government saving rates adjust residually to establish the macroeconomic saving-investment balance in each region.

4. The Transmission of Agricultural Productivity Shocks in General Equilibrium

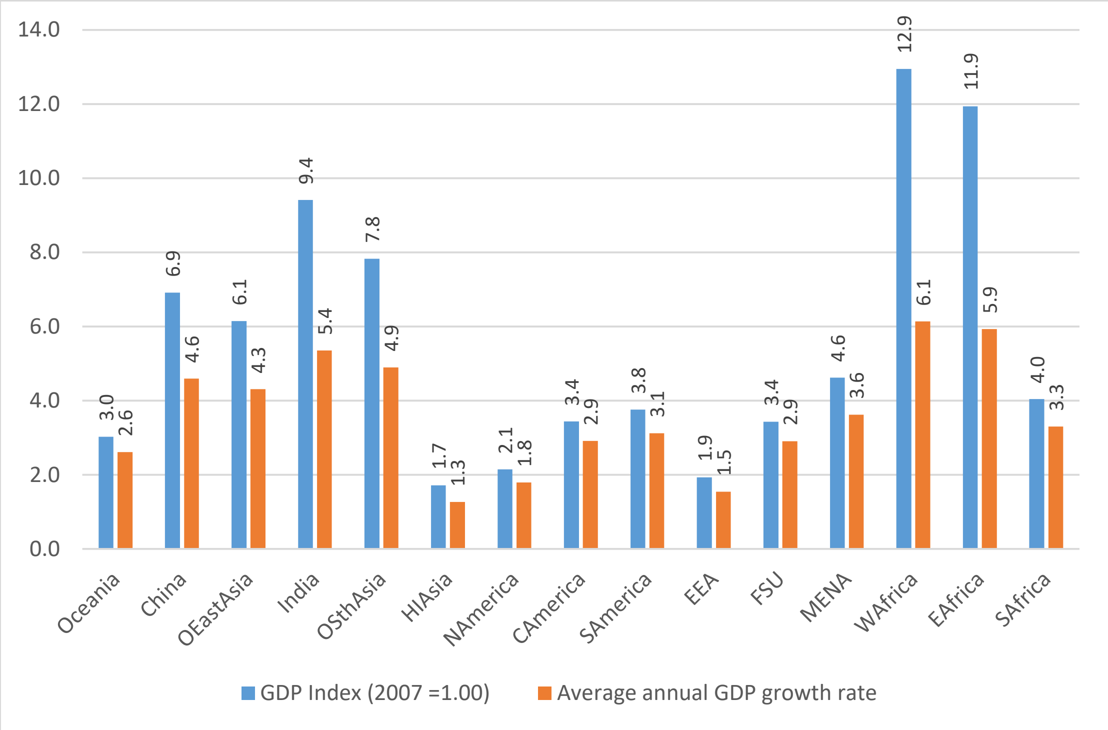
This section provides a systematic elaboration of the direct and indirect channels through which agricultural productivity shocks affect aggregate economic performance in the GLOBE model using the climate change impact scenario REF_HGEM of Rosegrant et al (2017) as a concrete example. All quantitative results presented here are expressed as percentage deviations from the reference scenario without climate change impacts on agricultural yields labelled REF_NoCC for 2050.

The IMPACT REF_NoCC and the initial IMPACT REF_HGEM climate change scenario prior to the incorporation of endogenous impacts on GDP cover the period 2007 to 2050 and use the same exogenous SSP2 (Shared Socio-Economic Pathway 2 – aka "middle of the road"[4]) assumptions about GDP growth (Figure 4) and population growth (Figure 5). The global population rises from 6.8 billion in 2010 to 9.1 billion in 2050, whereby a large share of the net increase is projected for Sub-Saharan Africa (+931 million), South Asia (+743 million) and the MENA region (+255 million).

The climate change scenario is based on RCP 8.5 (Representative Concentration Pathway 8.5) assumptions about the evolution of greenhouse gas concentration levels in the atmosphere. The global circulation model HadGEM2.es (Jones et al, 2011) has been used to generate regionally disaggregated climate projections for this concentration pathway. These climate change projections have in turn been linked to the DSSAT suite of crop models to generate time series of crop- and region-specific yield impacts (Robinson et al, 2015).

[4] O'Neill et al (2017), Dellink et al (2017).

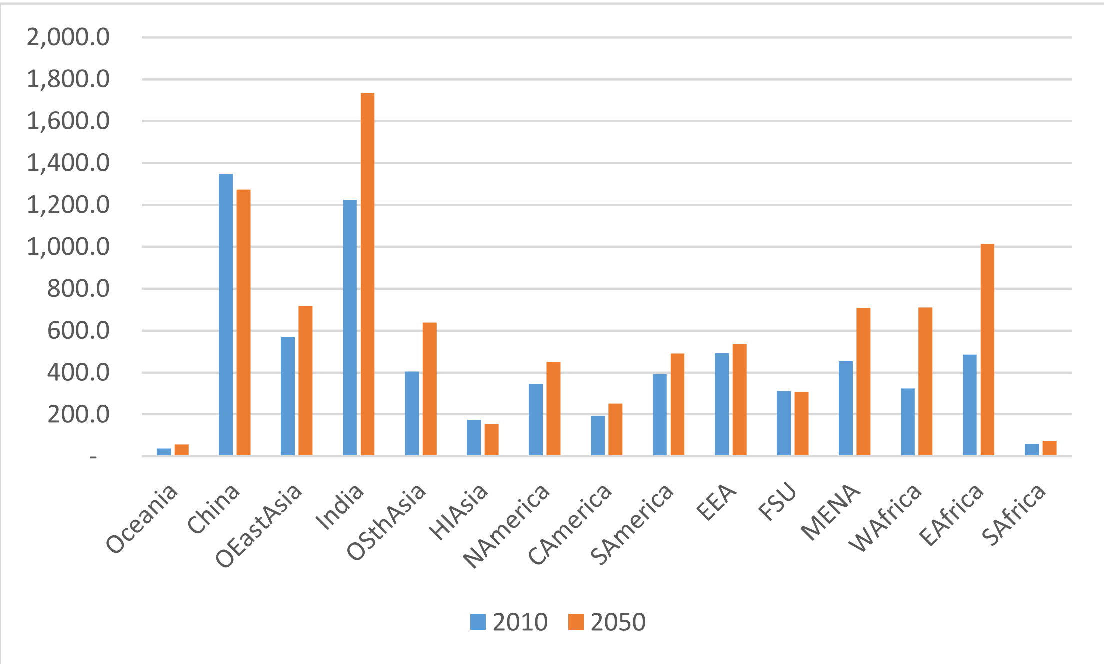
Figure 4: Baseline GDP Growth by Region 2007 to 2050 – SSP2



Source: Authors

Notes: GDP Index 2007 = 1.00 (e.g. China's 2050 baseline real GDP level is 4.6 times higher than in 2007; Average annual GDP growth rate 2007-2050 in percent

Figure 5: Population (millions) by Region 2010 and 2050 – SSP2



Source: Authors

Table 3: Change in IMPACT Producer Prices 2050 – REF_HGEM Scenario

	Rice	Wheat	OCereals	OilSeeds	SugarCane	OCrops	Cattle	OLvstkPrd	VegOils	Sugar
Oceania	25.6	20.1	8.1	18.8	31.9	16.9	4.4	3.3	3.8	8.9
China	25.6	20.1	51.4	37.3	28.3	15.3	4.2	6.7	4.6	8.9
OEastAsia	25.6	20.1	53.2	25.3	59.5	19.1	4.8	7.6	4.7	8.9
India	25.6	20.1	34.4	36.2	37.5	18.3	4.5	2.6	5.0	8.9
OSthAsia	25.6	20.1	46.4	21.7	45.5	19.9	4.3	2.9	4.0	8.9
HIAsia	25.6	20.1	6.4	31.8	35.7	15.2	5.0	5.7	3.7	8.9
NAmerica	25.6	20.1	49.6	32.8	50.6	17.9	5.0	5.5	4.2	8.9
CAmerica	25.6	20.1	46.9	30.7	62.1	20.4	4.9	6.3	4.2	8.9
SAmerica	25.6	20.1	49.5	34.5	53.6	21.2	4.9	6.0	4.3	8.9
EEA	25.6	20.1	21.5	16.9	42.2	17.5	4.7	4.9	3.9	8.9
FSU	25.6	20.1	22.3	18.5	54.9	20.1	4.7	4.0	3.7	8.9
MENA	25.6	20.1	21.1	27.5	32.5	17.1	4.0	5.2	4.7	8.9
WAfrica	25.6	20.1	31.6	42.6	56.6	18.9	4.1	6.1	5.8	8.9
EAfrica	25.6	20.1	37.5	42.4	52.8	19.7	4.5	3.4	5.8	8.9
SAfrica	25.6	20.1	51.5	38.3	38.5	18.6	4.6	6.3	4.2	8.9

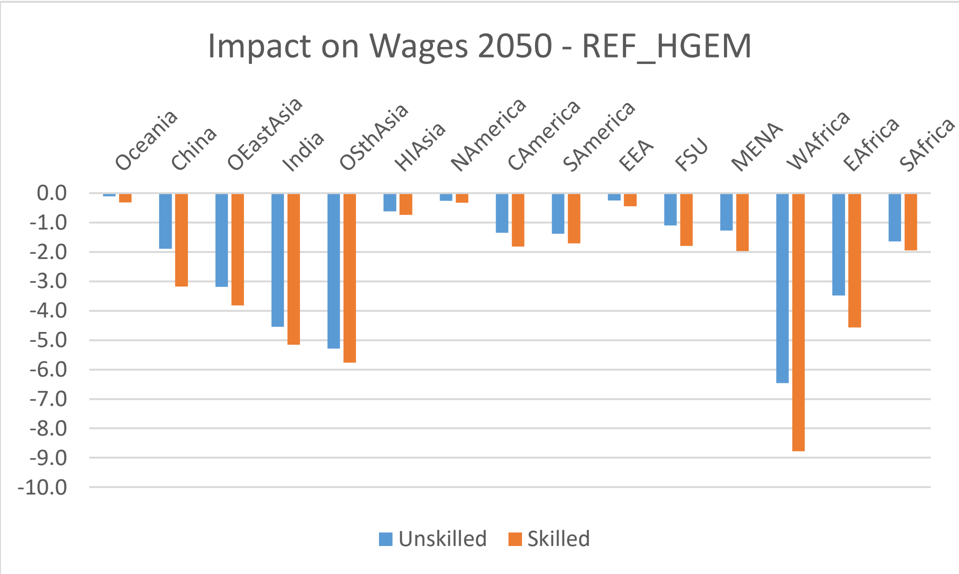
Source: Authors
Notes: Percentage deviation from 2050 REF_NoCC Scenario

The agricultural yield shocks considered in the REF_HGEM scenario enter the GLOBE model in the form of shifts of the factor productivity parameters in the agricultural production functions for all regions. These productivity shifts affect aggregate household income primarily via their impact on factor prices. In line with economic theory, equilibrium factor prices in the model are governed by the value of the marginal product of the corresponding factor, i.e. by the additional physical output produced by the last unit of the factor used evaluated at the output price. Thus, in the case of predominantly negative agricultural productivity shocks – as is the case under REF_HGEM – there are essentially two opposite forces affecting factor prices: On the one hand, the physical marginal products decline due to the adverse climate impacts on yields and this effect drags factor prices down. On the other hand, the resulting supply reductions for agricultural products drive agricultural prices up (Table 3) and *per se* lift factor prices upwards.

For labor wages and returns to capital the economy-wide net effect is unambiguously negative across all regions, as the marginal productivity effect dominates the output price effect (Figures 6 and 7). In the high-income regions, where the share of agriculture in GDP is low (recall Figure 1 above), the effects on wages and capital returns are very small, whereas in today's low-income regions, where the contribution of agriculture to GDP is still substantial towards 2050, these adverse factor price effects are far more pronounced.

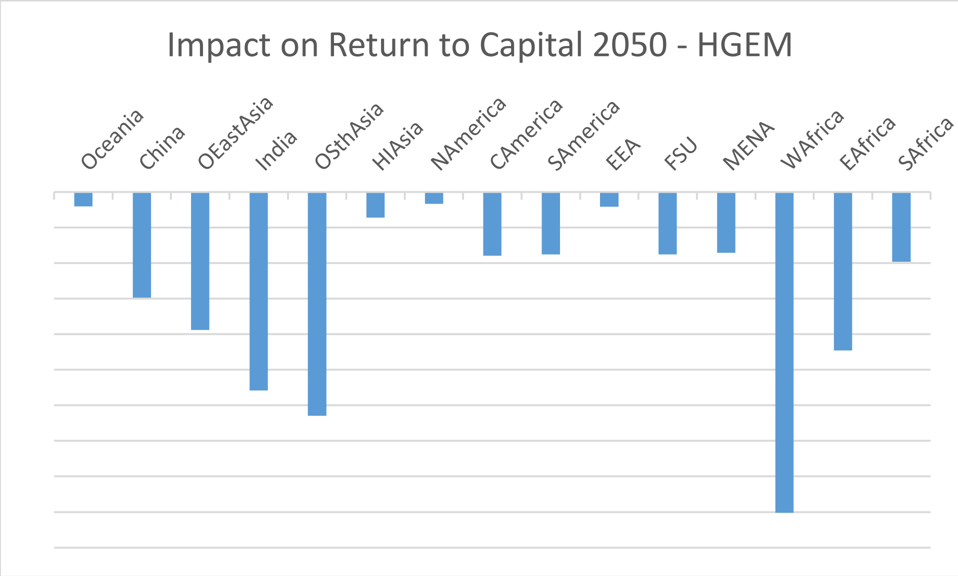
In contrast, the global increase in the prices for agricultural commodities drive agricultural land rents significantly upwards in all regions, as the price increases dominate the climate-change-induced reductions in the physical marginal productivity of land (Figure 8). The difference in the response of returns to labor versus returns to agricultural land is explained by the fact that labor is mobile between agricultural and non-agricultural activities, while agricultural land is an agriculture-specific quasi-fixed factor. More precisely, agricultural land can switch across agricultural activities in response to relative price changes in the model, but in contrast to labor, a rise in the prices of agricultural commodities relative to non-agricultural goods cannot pull land from non-agricultural sectors to agriculture. The model allows for endogenous changes in the supply of agricultural land in response to land rent changes, and in the linked IMPACT-GLOBE system, the land supply paths in GLOBE are calibrated to match the exogenous aggregate land use projections by region in IMPACT.

Figure 6: Change in Unskilled and Skilled Wage Rates - REF_HGEM Scenario



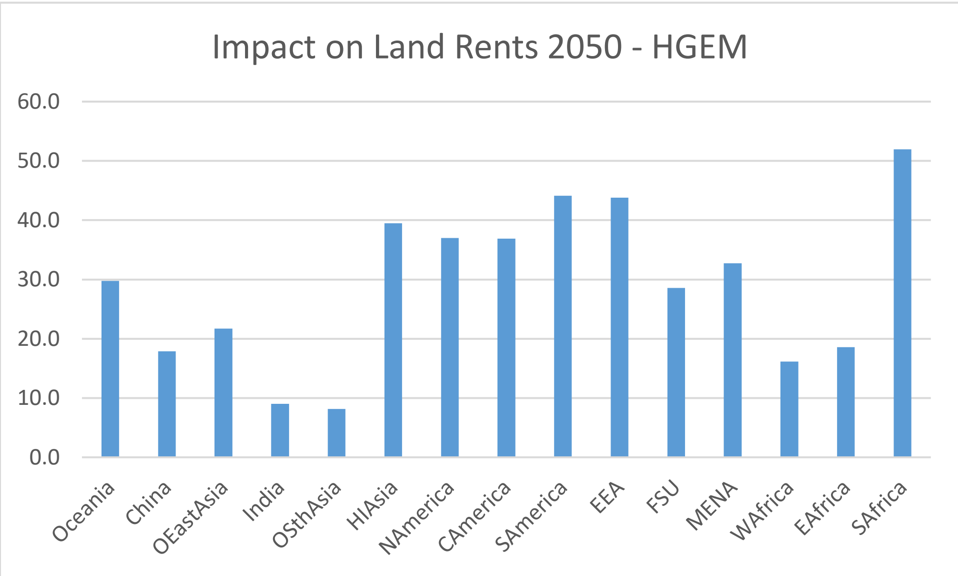
Source: Authors
Notes: Percentage deviation from 2050 REF_NoCC Scenario

Figure 7: Change in Rates of Return to Capital - REF_HGEM Scenario



Source: Authors
Notes: Percentage deviation from 2050 REF_NoCC Scenario

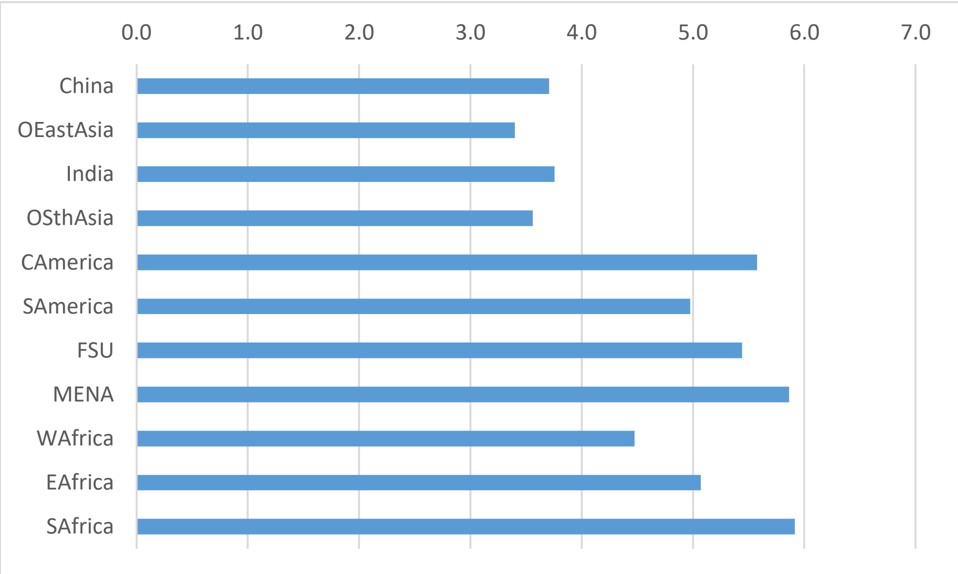
Figure 8: Change in Rates of Return to Land - REF_HGEM Scenario



Source: Authors
Notes: Percentage deviation from 2050 REF_NoCC Scenario

To get a full picture of the factor market responses triggered by the agricultural productivity shocks, it is instructive to look at the intersectoral employment reallocation effects. As agriculture employs predominantly unskilled labor, we focus on this skill group here. Figure 9 shows the simulated changes in unskilled employment in agriculture plus food-processing activities in 2050 relative to the REF_NoCC baseline for developing regions. In all regions, employment in the food-producing expands to some extent in response to the predominantly adverse impacts of climate change on agricultural yields, as additional labor and capital is required to satisfy the demand for food commodities, given that food demand is relatively price-inelastic. In economic terms, the rise in the relative price of food commodities, pulls labor and capital from non-food production to food production.

Figure 9: Change in Unskilled Employment in Agricultural and Food Processing Sectors for Developing Regions - REF_HGEM Scenario



Source: Authors
Notes: Percentage deviation from 2050 REF_NoCC Scenario

However, the net employment reallocation effects reported in Figure 9 are also influenced by the international trade effects of climate change, which can either reinforce or diminish this resource pull effect.

The resulting effects on household income at decadal intervals is shown in Table 4. As land rents account only for a small fraction of total factor income in all regions, the size orders of the aggregate household income effects are largely determined by the changes in wages and capital returns.

Table 4: Change in Aggregate Household Income – REF_HGEM Scenario

	2010	2020	2030	2040	2050
Oceania	0.0	0.0	0.0	-0.1	-0.1
China	0.0	-0.5	-1.2	-1.9	-2.5
OEastAsia	0.0	-0.5	-1.2	-2.1	-3.1
India	0.0	-0.7	-1.6	-2.9	-4.4
OSthAsia	0.0	-0.7	-1.6	-2.9	-4.6
HIAsia	0.0	-0.1	-0.3	-0.4	-0.6
NAmerica	0.0	0.0	-0.1	-0.1	-0.2
CAmerica	0.0	-0.3	-0.6	-1.0	-1.5
SAmerica	0.0	-0.2	-0.5	-0.8	-1.2
EEA	0.0	-0.1	-0.1	-0.2	-0.3
FSU	0.0	-0.2	-0.6	-1.0	-1.5
MENA	0.0	-0.3	-0.7	-1.2	-1.8
WAfrica	0.0	-1.3	-3.0	-5.2	-7.5
EAfrica	0.0	-0.7	-1.5	-2.7	-4.0
SAfrica	0.0	-0.3	-0.7	-1.1	-1.6

Source: Authors
Notes: Percentage deviation of household income from REF_NoCC Scenario

Table 5 reports the corresponding impacts on real GDP by region. Not surprisingly, in percentage terms, the GDP effects are closely similar to the household income effects. As shown earlier in Figure 2, nearly 95 percent of the variation in the real income effects across regions can be "explained" by the variation in the baseline agricultural shares in GDP.

Table 5: Change in Real GDP – REF_HGEM Scenario

	2010	2020	2030	2040	2050
Oceania	0.0	0.0	0.0	0.0	-0.1
China	0.0	-0.4	-1.0	-1.7	-2.3
OEastAsia	0.0	-0.5	-1.2	-2.1	-3.1
India	0.0	-0.6	-1.5	-2.7	-4.2
OSthAsia	0.0	-0.7	-1.5	-2.9	-4.6
HIAsia	0.0	-0.1	-0.3	-0.4	-0.6
NAmerica	0.0	0.0	-0.1	-0.1	-0.1
CAmerica	0.0	-0.2	-0.6	-1.0	-1.5
SAmerica	0.0	-0.2	-0.5	-0.8	-1.2
EEA	0.0	0.0	-0.1	-0.1	-0.2
FSU	0.0	-0.2	-0.6	-1.0	-1.5
MENA	0.0	-0.3	-0.7	-1.2	-1.8
WAfrica	0.0	-1.3	-3.0	-5.1	-7.5
EAfrica	0.0	-0.6	-1.5	-2.6	-4.0
SAfrica	0.0	-0.3	-0.7	-1.1	-1.6

Source: Authors
Notes: Percentage deviation of GDP from REF_NoCC Scenario

5. Results by Scenario

5.1 Overview of Scenarios

Table 6 provides a full list of the simulation scenarios considered in this project and serves as a guide to the scenario labels used in the following figures and tables. Detailed descriptions of the scenario assumptions and their implementation in IMPACT are given in Rosegrant et al (2017).

Table 6: Summary of Baseline, Policy and Investment Scenarios

Scenario Grouping	Scenario	Scenario Description
Baseline	REF_HGEM	Baseline reference scenario with HGEM 8.5 future climate (primary baseline scenario)
	REF_NoCC	Baseline reference scenario with constant 2005 climate
	REF_IPSL	Baseline reference scenario with IPSL 8.5 future climate
Productivity Enhancement	MED	Medium increase in investment across the CGIAR portfolio
	HIGH	High increase investment across the CGIAR portfolio
	HIGH+NARS	High increase in investment across the CGIAR portfolio plus complementary NARS investments
	HIGH+RE	High increase in investment across the CGIAR portfolio plus increased research efficiency
	REGION	Regionally-focused high increase in CGIAR investments Targets the highest investments to South Asia and Sub-Saharan Africa with medium levels of investment increase in Latin America, and East Asia
Improved Water Resource Management	IX_HGEM	Investments targets to expand irrigation in the developing world (HGEM RCP 8.5)
	IX_NoCC	IX scenario under a constant 2005 climate
	IX_IPSL	IX scenario under an IPSL RCP 8.5 future climate
	IX+WUE_HGEM	Irrigation expansion plus water-use efficiency investments (HGEM RCP 8.5)
	IX+WUE_NoCC	IX+WUE under a constant 2005 climate
	IX+WUE_IPSL	IX+WUE under an IPSL RCP 8.5 future climate
	ISW_HGEM	Investments targeted to Increased soil water holding capacity (HGEM RCP 8.5)
	ISW_NoCC	ISW under a constant 2005 climate
	ISW_IPSL	ISW under an IPSL RCP 8.5 future climate
Infrastructure and Agricultural Marketing	RMM	Scenario based on infrastructure improvements to improve market efficiency through the reduction of transportation costs and marketing margins
Comprehensive Investment	COMP	This comprehensive scenario is a combination of 4 scenarios: HIGH+RE; IX+WUE; ISW; and RMM (HGEM RCP 8.5)
	COMP_NoCC	COMP scenario under a constant 2005 climate
	COMP_IPSL	COMP scenario under an IPSL RCP 8.5 future climate

Source: Rosegrant et al (2017: Table 2.10).

5.2. Household Income

Figures 10 to 15 display the real income changes for aggregate developing regions for the year 2050 relative to the corresponding REF[5] scenario. The climate-change-related agricultural productivity shifts under the climate change impact scenario are transmitted to aggregate household income primarily via their impact on factor prices. In the high-income regions, where the share of agriculture in GDP is low, the effects on wages and capital returns are small, whereas in today's low-income regions, where the contribution of agriculture to GDP is still substantial towards 2050, these adverse factor price effects are far more pronounced. The global increase in the prices for agricultural commodities drive land rents significantly upwards in all regions, as the price increases dominate the climate-change-induced reductions in the physical marginal productivity of land. As land rents account only for a small fraction of total factor income in all regions, the size orders of the aggregate household income effects are largely determined by the changes in wages and capital returns. The real income effects are also affected by aggregate terms-of-trade effects. However, the terms of trade deviations from the baseline reported in Table 7 below are generally moderate to small.

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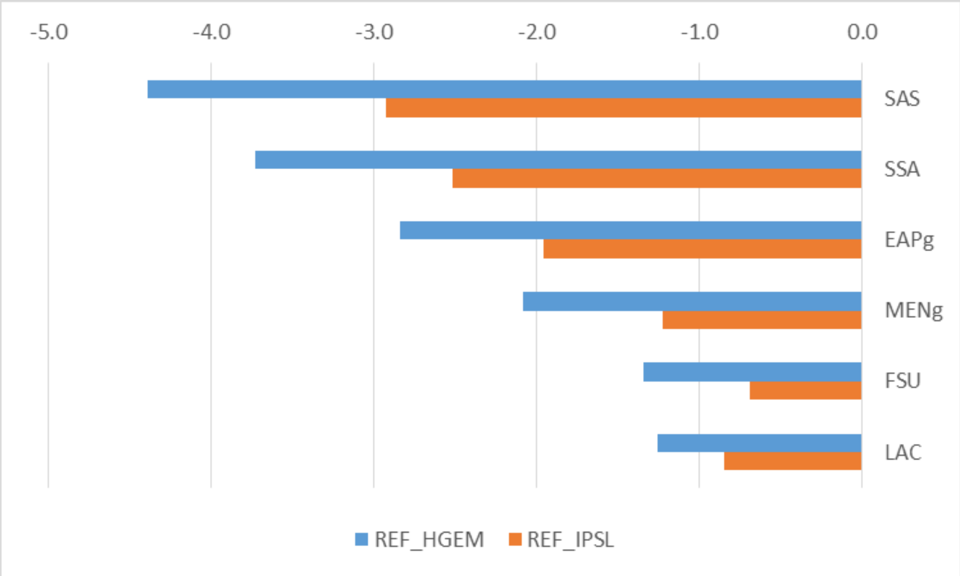
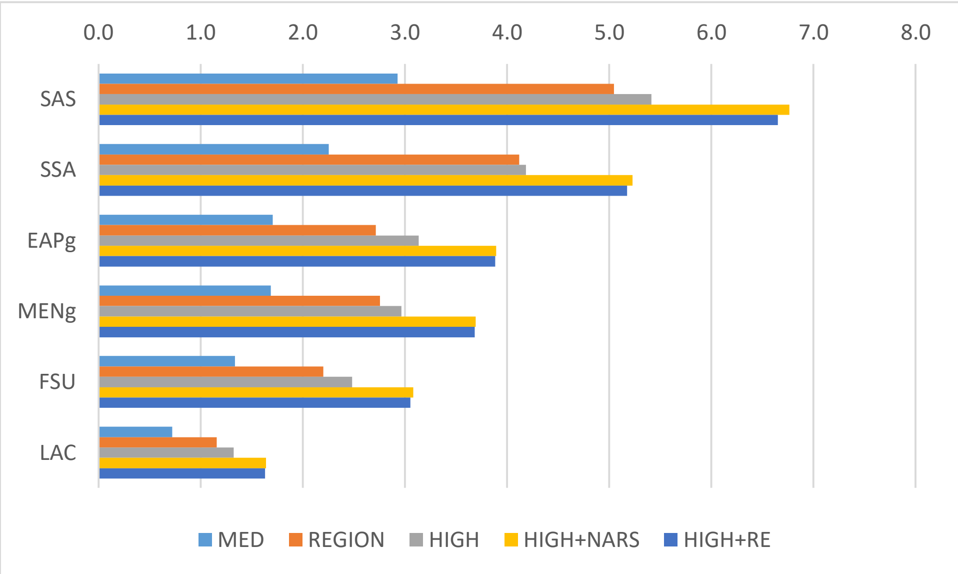
[5] To be explicit: For scenarios REF_HGEM, REF_IPSL, IX_NoCC, IX+WUE_NoCC, ISW_NoCC and COMP_NoCC the percentage changes reported in the following figures and tables are relative to the REF_NoCC scenario.
For scenarios MED, REGION, HIGH, HIGH+NARS, HIGH+RE, IX_HGEM, IX+WUE_HGEM, ISW_HGEM, RMM and COMP_HGEM, the corresponding reference scenario is REF_HGEM.
Finally, for IX_IPSL, IX+WUE_IPSL, ISW_IPSL and COMP_IPSL the baseline for comparison is the REF_IPSL scenario.

Figure 10: Change in Household Income in 2050 – Baseline Scenarios



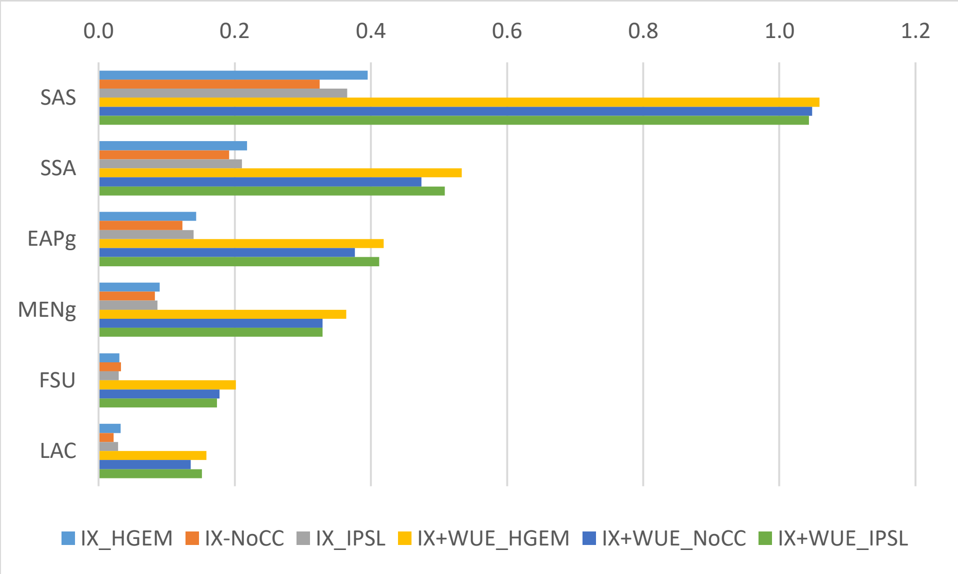
Source: Authors
Notes: Percentage change from REF_NoCC 2050

Figure 11: Change in 2050 Household Income - Productivity Enhancement Scenarios



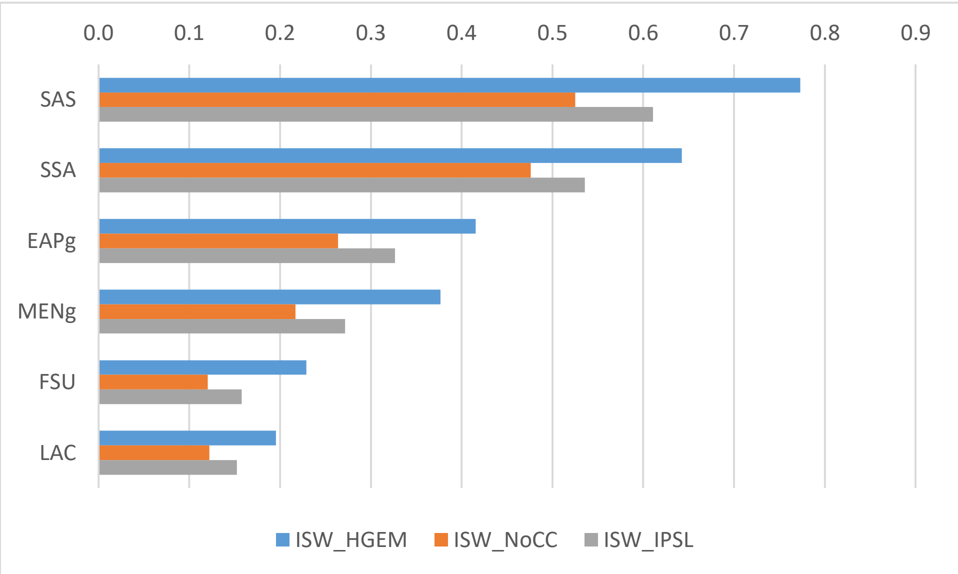
Source: Authors
Notes: Percentage change from REF_HGEM 2050

Figure 12 Change in 2050 Household Income – Irrigation Expansion Scenarios



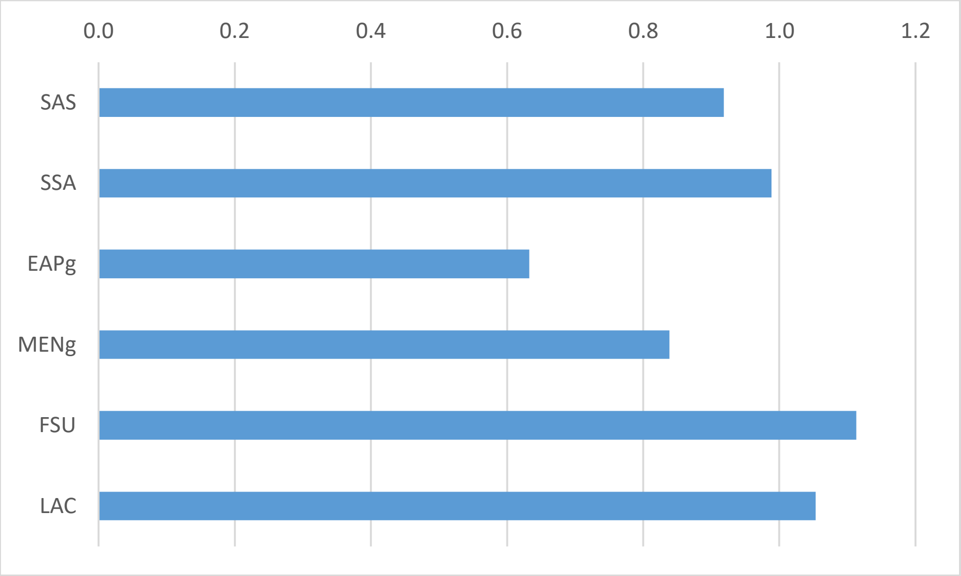
Source: Authors
Notes: Percentage change from corresponding REF_* scenario 2050

Figure 13: Change in 2050 Household Income – Increased Soil Water Scenarios



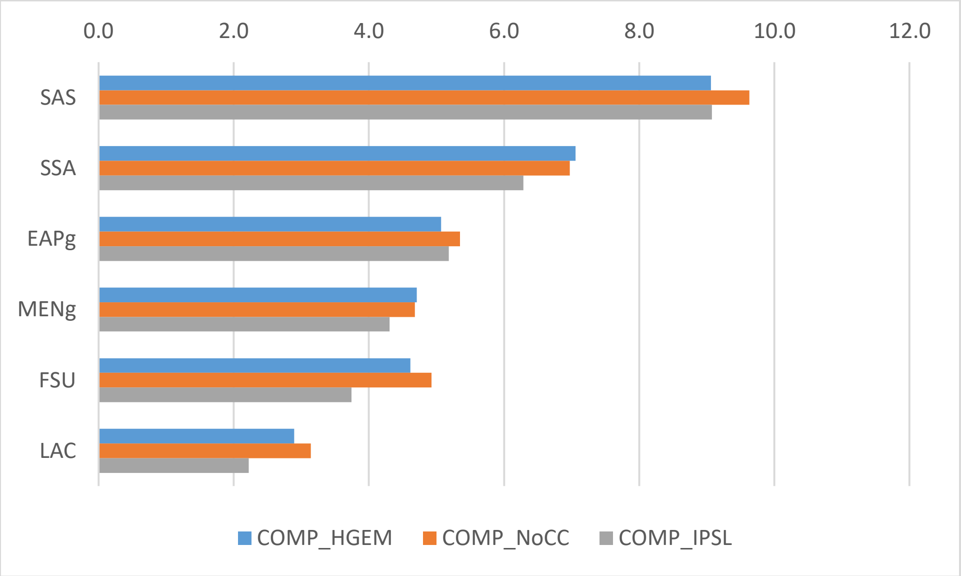
Source: Authors
Notes: Percentage change from corresponding REF_* scenario 2050

Figure 14: Change in 2050 Household Income – Infrastructure and Marketing Scenarios



Source: Authors
Notes: Percentage change from REF_HGEM 2050

Figure 15: Change in 2050 Household Income – Comprehensive Investment Scenarios



Source: Authors
Notes: Percentage change from corresponding REF_* scenario 2050

Table 7: Terms of Trade Impact 2050 by Region

	Oceania	China	OEastAsia	India	OSthAsia	HIAsia	NAmerica	CAmerica	SAmerica	EEA	FSU	MENA	WAfrica	EAfrica	SAfrica
REF_HGEM	0.5	-0.3	0.0	0.1	0.0	-0.4	0.9	-0.2	2.0	-0.1	-0.2	-0.7	0.1	-0.1	0.0
REF_IPSL	0.3	-0.2	0.0	0.1	0.1	-0.3	0.5	-0.1	1.3	0.0	-0.2	-0.4	0.1	-0.1	0.0
MED	-0.5	0.1	0.0	0.0	-0.1	0.2	-0.4	0.0	-0.6	0.0	0.1	0.4	0.0	0.1	0.0
REGION	-0.9	0.1	0.0	-0.1	-0.2	0.3	-0.6	0.0	-1.0	0.0	0.2	0.7	-0.1	0.1	0.0
HIGH	-0.9	0.1	0.0	-0.1	-0.2	0.3	-0.7	0.0	-1.0	0.0	0.2	0.7	0.0	0.2	0.0
HIGH+NARS	-1.2	0.1	0.0	-0.1	-0.3	0.4	-0.8	0.0	-1.3	0.0	0.3	0.9	0.0	0.2	-0.1
HIGH+RE	-1.1	0.1	0.0	-0.1	-0.3	0.4	-0.8	0.0	-1.3	0.0	0.3	0.9	0.0	0.2	0.0
IX_HGEM	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
IX_NoCC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
IX_IPSL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
IX+WUE_HGEM	-0.1	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0
IX+WUE_NoCC	-0.1	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0
IX+WUE_IPSL	-0.1	0.0	0.0	-0.1	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0
ISW_HGEM	-0.1	0.0	0.0	0.0	0.0	0.1	-0.1	0.0	-0.2	0.0	0.0	0.1	0.0	0.0	0.0
ISW_NoCC	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	-0.2	0.0	0.0	0.1	0.0	0.0	0.0
ISW_IPSL	-0.1	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	-0.2	0.0	0.0	0.1	0.0	0.0	0.0
RMM	0.0	0.0	0.0	-0.1	-0.1	0.1	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	-0.1
COMP_HGEM	-1.2	0.1	0.0	-0.2	-0.4	0.5	-0.8	0.0	-1.5	0.0	0.3	1.0	0.0	0.2	-0.1
COMP_NoCC	-0.9	-0.1	-0.1	-0.3	-0.5	0.4	-0.6	-0.1	-1.3	0.0	0.4	0.9	0.0	0.2	-0.2
COMP_IPSL	-1.0	0.0	-0.1	-0.2	-0.4	0.4	-0.7	0.0	-1.4	0.0	0.4	1.0	0.0	0.2	-0.1

Source: Authors

Notes: Percentage change from corresponding REF_* scenario 2050

5.3. Real Absorption and Consumer Welfare

Tables 8 and 9 report aggregate welfare deviations from the corresponding baseline by GLOBE region for 2050 as measured by changes in real absorption and the Hicksian equivalent variation respectively. The Hicksian equivalent variation (EV) is a money-metric measure of the change in utility due to an economic shock that changes the vector of consumer prices from P^0 to P^1. The EV is defined as the hypothetical change in income devoted to consumption in the *pre-shock* situation that would generate the same welfare effect as the shock considered. Or stated differently, it is the amount that would have to be deducted from (negative shock) or added to (positive shock) a household's consumption expenditure in the absence of the shock to make this household as well off as in the presence of the shock.

To derive EV formally, let V(P,E) denote the indirect utility function dual to the direct utility function U(C), where E denotes consumption expenditure, C is the vector of consumption quantities and U(V) denotes utility. The indirect utility function gives the maximum utility an optimizing household can reach when faced with consumer price vector P and available monetary expenditure E, given the budget constraint E = P'C. The indirect utility function is derived by inserting the Marshallian demand functions C(P,E) – which are the solutions to the problem of maximizing U(C) subject to the budget constraint – back into the direct utility function. Inversion of the direct utility function yields the expenditure function E(U,P), which by construction returns the expenditure required to reach any welfare level U for any consumer price vector P.

Using these welfare-theoretical concepts, the general formula for the measurement of the equivalent variation takes the form

$$EV = E(U^1, P^0) - E^0 = E(V(P^1, U^1), P^0) - E^0 \quad , \qquad (1)$$

where superscripts 0 and 1 refer to the pre- and post-shock levels of the corresponding variables respectively.

In GLOBE, the direct utility function for household type h in region r takes the Stone-Geary form

$$U_{h,r} = \prod_c \left(QCD_{c,h,r} - qcdconst_{c,h,r}\right)^{\beta_{c,h,r}} \quad , \qquad (2)$$

where c is an index over commodities, β and qcdconst are parameters, and the QCD (~ C) denote consumption quantities. The Marshallian demand functions resulting from utility maximization subject to household budget constraint are

$$QCD_{c,h,r} = qcdconst_{c,h,r} + \beta_{c,h,r} * \left(HEXP_{h,r} - \sum_c \left(qcdconst_{c,h,r} * PQD_{c,r}\right)\right) / PQD_{c,r} \quad , \tag{3}$$

where HEXP (~E) and PQD (~P) denote consumption expenditure and consumer prices respectively. Inserting (3) into (2) yields the indirect utility functions

$$V(PQD, HEXP)_{h,r} = \prod_c \left(\frac{\beta_{c,h,r}}{PQD_{c,r}}\right)^{\beta_{c,h,r}} \left(HEXP_{h,r} - \sum_c \left(qcdconst_{c,h,r} * PQD_{c,r}\right)\right) \quad . \tag{4}$$

Solving (4) for HEXP (~E), the expenditure functions are found to take the form

$$E(U, PQD)_{h,r} = U \prod_c \left(\frac{\beta_{c,h,r}}{PQD_{c,r}}\right)^{-\beta_{c,h,r}} + \sum_c \left(qcdconst_{c,h,r} * PQD_{c,r}\right) \quad . \tag{5}$$

Using (5) and (4) in equation (1) yields the operational formula for the determination of the equivalent variation under Stone-Geary preferences:

$$\begin{aligned} EV_{h,r} = & \prod_c \left(\frac{PQD^0_{c,r}}{PQD^1_{c,r}}\right)^{\beta_{c,h,r}} \left(HEXP^1_{h,r} - \sum_c \left(qcdconst_{c,h,r} * PQD^1_{c,r}\right)\right) \\ & + \sum_c qcdconst_{c,h,r} * PQD^0_{c,r} \\ & - HEXP^0_{h,r} \quad . \end{aligned} \tag{6}$$

The equivalent variation is a theoretically neat measure of welfare changes due to changes in *private* consumption in each period, but does not take account of potential shock-induced changes in public expenditure and net investment. Therefore, the EV would be a complete measure of welfare changes only if government expenditure generates *no* welfare at all and if changes investment activity (that entail changes in future consumption) would be irrelevant from a welfare perspective.

As neither of these conditions holds, the change in real aggregate absorption – that is the total basket of goods and services used for private and public final consumption and investment within a given period and region – is occasionally used as a more comprehensive (ad hoc) measure of welfare change in CGE analysis. Thus, Table 8 reports results for changes in this alternative welfare indicator. The EV and absorption measures are closely correlated with each other (e.g. $R^2 = 0.97$ for the REF_HGEM deviations from the baseline in 2050). Unsurprisingly, the EV welfare measure is also highly correlated with the reported real GDP deviations from the baseline (e.g. $R^2 = 0.92$ for REF_HGEM). In percentage change terms, the welfare losses measured by the EV are lower than the reported GDP losses across the board, since the EV measure takes substitution effects in household consumption triggered by relative price changes into account, while the reported GDP figures measure income in terms of an unchanged consumption basket.

Table 8: Impact on Real Absorption 2050 by GLOBE Region

	Oceania	China	OEastAsia	India	OSthAsia	HIAsia	NAmerica	CAmerica	SAmerica	EEA	FSU	MENA	WAfrica	EAfrica	SAfrica
REF_HGEM	0.1	-0.8	-0.6	-0.7	-0.6	-0.2	0.0	-0.3	-0.1	-0.1	-0.4	-0.6	-1.6	-0.9	-0.2
REF_IPSL	0.1	-0.5	-0.4	-0.5	-0.3	-0.1	0.0	-0.3	-0.1	-0.1	-0.2	-0.4	-1.1	-0.6	-0.2
MED	0.1	0.5	0.4	0.5	0.5	0.1	0.0	0.1	0.1	0.1	0.4	0.5	1.1	0.6	0.1
REGION	0.2	0.8	0.5	0.8	0.9	0.2	0.0	0.2	0.2	0.2	0.6	0.8	2.1	1.0	0.1
HIGH	0.2	0.9	0.7	0.9	1.0	0.2	0.0	0.3	0.3	0.2	0.7	0.9	2.1	1.1	0.2
HIGH+NARS	0.2	1.1	0.8	1.1	1.3	0.3	0.0	0.3	0.3	0.3	0.9	1.1	2.7	1.3	0.2
HIGH+RE	0.2	1.2	0.8	1.1	1.2	0.3	0.0	0.3	0.3	0.3	0.9	1.1	2.7	1.3	0.2
IX_HGEM	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0
IX_NoCC	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0
IX_IPSL	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0
IX+WUE_HGEM	0.0	0.1	0.1	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.0
IX+WUE_NoCC	0.0	0.1	0.1	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.1	0.0
IX+WUE_IPSL	0.0	0.1	0.1	0.2	0.2	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.2	0.1	0.0
ISW_HGEM	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.3	0.1	0.0
ISW_NoCC	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.1	0.0
ISW_IPSL	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.1	0.0
RMM	0.0	0.2	0.5	0.4	0.9	0.0	0.0	0.4	0.5	0.0	0.4	0.3	0.8	0.4	1.3
COMP_HGEM	0.2	1.5	1.4	1.7	2.5	0.3	0.0	0.9	0.9	0.3	1.3	1.5	3.9	2.0	1.6
COMP_NoCC	0.1	1.8	1.6	1.9	3.0	0.2	0.0	1.0	1.2	0.2	1.5	1.6	4.2	2.2	1.8
COMP_IPSL	0.1	1.7	1.1	1.5	1.9	0.3	0.0	0.5	0.6	0.2	1.2	1.4	3.3	1.7	0.4

Source: Authors
Notes: Percentage change from corresponding REF_* scenario 2050

Table 9: Impact on Household Welfare 2050 by GLOBE Region

	Oceania	China	OEastAsia	India	OSthAsia	HIAsia	NAmerica	CAmerica	SAmerica	EEA	FSU	MENA	WAfrica	EAfrica	SAfrica
REF_HGEM	0.0	-1.3	-0.9	-1.4	-1.1	-0.3	0.0	-0.5	-0.3	-0.2	-0.6	-0.8	-2.3	-1.3	-0.5
REF_IPSL	0.0	-0.9	-0.7	-0.9	-0.6	-0.2	0.0	-0.4	-0.2	-0.1	-0.3	-0.5	-1.6	-0.9	-0.4
MED	0.2	0.8	0.5	0.9	0.9	0.2	0.0	0.2	0.2	0.2	0.6	0.6	1.5	0.8	0.2
REGION	0.3	1.3	0.8	1.5	1.6	0.3	0.0	0.4	0.4	0.3	0.9	1.0	2.8	1.4	0.3
HIGH	0.3	1.5	1.0	1.6	1.7	0.4	0.0	0.4	0.4	0.3	1.0	1.1	2.8	1.5	0.4
HIGH+NARS	0.4	1.8	1.2	2.0	2.2	0.5	0.1	0.5	0.5	0.4	1.3	1.4	3.5	1.9	0.5
HIGH+RE	0.4	1.8	1.2	2.0	2.1	0.5	0.1	0.5	0.5	0.4	1.3	1.4	3.5	1.9	0.5
IX_HGEM	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.0
IX_NoCC	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0
IX_IPSL	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.0
IX+WUE_HGEM	0.0	0.2	0.1	0.3	0.3	0.1	0.0	0.1	0.0	0.0	0.1	0.1	0.3	0.2	0.1
IX+WUE_NoCC	0.0	0.1	0.1	0.3	0.4	0.1	0.0	0.1	0.0	0.0	0.1	0.1	0.3	0.2	0.1
IX+WUE_IPSL	0.0	0.2	0.1	0.3	0.3	0.1	0.0	0.1	0.0	0.0	0.1	0.1	0.3	0.2	0.1
ISW_HGEM	0.0	0.2	0.1	0.2	0.2	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.4	0.2	0.1
ISW_NoCC	0.0	0.1	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.3	0.1	0.0
ISW_IPSL	0.0	0.1	0.1	0.2	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.3	0.1	0.0
RMM	0.0	0.3	0.6	0.5	1.0	0.0	0.0	0.6	0.6	0.0	0.6	0.4	0.8	0.6	1.8
COMP_HGEM	0.4	2.4	1.9	2.9	3.7	0.6	0.1	1.2	1.2	0.4	2.0	2.0	4.9	2.8	2.5
COMP_NoCC	0.3	2.7	2.0	3.1	4.2	0.4	0.0	1.3	1.5	0.3	2.2	2.0	4.9	2.9	2.7
COMP_IPSL	0.3	2.6	1.6	2.7	3.1	0.4	0.0	0.7	0.9	0.3	1.7	1.7	4.2	2.4	0.8

Source: Authors

Notes: Hicksian Equivalent Variation in percent of corresponding REF_* scenario household expenditure

6. Concluding Remarks

The basic rationale for linking IFPRI's global agricultural partial equilibrium model IMPACT with a dynamic multi-region general equilibrium model is to capture the advantages of both modelling approaches. The linked modelling framework enables a quantitative analysis of the wider implications of agricultural sector scenario projections generated by IMPACT by taking systematic account of linkages between agriculture and the rest of the economy and allows a rigorous theory-grounded general equilibrium welfare analysis of shocks to agriculture. At the same time this framework supports a more detailed agricultural commodity disaggregation and a far finer spatial resolution on the supply side than is feasible in a stand-alone global CGE model.

As the results for the Sub-Sahara African and South Asian reported in sections 4 and 5 clearly indicate, the incorporation of general equilibrium effects on aggregate GDP and thus household income triggered by shocks to the agricultural sector make a significant difference to the results for the regions that matter most from a food security perspective.

There is considerable scope for the further development and refinement of the IMPACT-GLOBE linkage approach in future applications. A first and relatively straightforward extension concerns the specification of water use in non-agricultural production within IMPACT. The water demand module of IMPACT presently uses disaggregated projections of value-added growth for manufacturing industries and energy sectors from the MIT EPPA6 model (Chen et al, 2015) to generate projections for industrial water demand by region. Replacing the EPPA projections by the corresponding downscaled scenario-specific GLOBE projections is an obvious step to enhance the internal consistency of the linked system.

A related conceivable extension is the incorporation of potential direct effects of acute water scarcity events on non-agricultural production and economic growth.[6] In line with common practice, the IMPACT water allocation mechanism gives top priority to domestic household demand, second priority to industrial and livestock demand, and remaining water is available for irrigation (Robinson et al, 2015). Thus, in instances where a water shortage exceeds the notional irrigation water demand (i.e. situations where a water deficit cannot be fully absorbed by cutting irrigation) industrial water supplies are rationed in the model, yet the impacts of

[6] See Sadoff et al (2015) for a recent comprehensive study of the connections between water security and economic growth.

these water supply cuts on both agricultural and non-agricultural value-added generation, and hence GDP growth are not captured in stand-alone IMPACT simulations. The linked IMPACT-GLOBE system in its current form takes account of the effects of irrigation water shortfalls on GDP. The inclusion of a link from instances of industrial water supply shortages detected by IMPACT to industrial production in GLOBE would appear desirable in principle but is a non-trivial task in practice. As Hertel and Liu (2016) note in this respect, "modelling the impacts of water scarcity in a global CGE framework is not for the faint of heart".[7] A recent study by Roson (2017) for the World Bank (2016) High and Dry Report provides an interesting effort to incorporate the impacts of water rationing on non-agricultural sectors into a global CGE model in a parsimonious manner. Prior to implementing a corresponding modification of the linked IMPACT-GLOBE system along these lines, it appears worth analyzing how frequent (and in which locations) instances of industrial water supply shortages actually occur in plausible IMPACT scenario simulations.

While the simulation results reported in the present paper are based on a calibration of GLOBE to the GTAP8 database, the model has meanwhile been updated and re-calibrated using the new GTAP9 database (Aguiar, Narayanan and McDougall, 2016) released in autumn 2016. GTAP9 contains a satellite database developed by Peters (2016), which disaggregates the electricity sector in each GTAP region by generation technology for the benchmark year 2011. This new database opens up potential new avenues for further analysis of the energy-water-food nexus with the linked IMPACT_GLOBE system that would move beyond the initial exploratory study by Ringler et al (2016). Progress in this direction would require transformation of the power sector representation in GLOBE from a top-down to a hybrid bottom-up top- down specification, and the development of a plausible dynamic baseline for the evolution of the power mix by country up to 2050.

Finally, given that Rosegrant et al (2017) provides cost estimates for all the agricultural investment measures under consideration, it suggests itself to include the additional investment costs of such measures in the CGE-based economy-wide analysis in future applications. This would enable a cost-benefit comparison of alternative investment programs, which takes into account that from a global macro perspective the additional investments compete with other investments for available savings. It would also require scenario developers to articulate

[7] For the conceptual and practical challenges of capturing water resource constraints adequately in CGE models see also Liu, Hertel and Taheripour (2016) and

whether the assumed additional investments in any region are meant to be financed via domestic savings or via transfers from other regions.

Appendix A: Technical Documentation of GLOBE-Energy

A.1. Notation

A.1.1. Sets and Subsets

a	Activities
acx(a,r)	Activities active in r
aqx(a,r)	Activities and regions with substitutability between value added and intermediates
aqxn(a,r)	Activities and regions with no substitutability between value added and intermediates
aene(a)	Activities with KLEM technology
c	Commodities
ct2(c)	Trade margin commodities
ce(c,r)	Commodities exported by r
cen(c,r)	Commodities not exported by r
cer(c,w,r)	Commodities exported by r to w
cm(c,r)	Commodities imported by r
cmn(c,r)	Commodities not imported by r
cmr(w,c,r)	Commodities imported by r from w
cmrs(w,c,r)	Commodities where share of origin w in r's total imports of c is non-zero but 'small'
cms(c,r)	Commodities imported by r with at least one small origin share
cmrl(w,c,r)	Commodities where share of origin w in r's total imports of c is not 'small'
cml(c,r)	Commodities imported by r with at least one non-small origin share
cx(c,r)	Commodities produced in r
cxn(c,r)	Commodities not produced in r and imported by r
cd(c,r)	Commodities with no production in r for the home market
cdn(c,r)	Commodities NOT produced and demanded domestically
cintd(c,r)	Commodities with intermediate input demand by region r
cener(c)	Energy commodities
cnener(c)	Non-energy commodities
f	Production factors
spfac(f)	Sector-specific factors
r	Regions
rgn(r)	Regions without globe
ref(r)	Reference region(s) for numeraire choice
w	Partner regions in bilateral transactions
wgn(w)	Partner regions in bilateral transactions without globe

A.1.2. Variables

1. Trade Block

1.1. Exports Block

PER(c,w,r)	Domestic price of exports of c from r to w
PE(c,r)	Domestic price of region r's exports of c
PWE(c,w,r)	World price of exports of c from r to w
PD(c,r)	Consumer price for domestic supply of commodity c
QER(c,w,r)	Exports of c from r to w
QE(c,r)	Exports of c from r
QD(c,r)	Domestic demand for commodity c
ER(r)	Exchange rate (domestic r / reference region)

1.2. Trade Margins

PT(ct2,r)	Price of imported transport services (same price to imports from all regions)
QT(w,c,r)	Quantity of margin services for total imports by r from region w

1.3. Imports Block

PMR(w,c,r)	Domestic price of imports of c from w to r
PM(c,r)	Domestic price of imports of commodity c to region r
PML(c,r)	Domestic price of imports of c to r from regions with small shares

PMS(c,r)	Domestic price of imports of c to r from regions with large shares
PWM(w,c,r)	CIF price of imports of commodity c from region w to r
PWMFOB(w,c,r)	FOB price of imports of commodity c from region w to r
QQ(c,r)	Supply of composite (Armington) commodity c
QM(c,r)	Imports of commodity c
QML(c,r)	Supply of composite import from large share regions
QMS(c,r)	Supply of composite import from small share regions
QMR(w,c,r)	Imports of c from region to r
PQS(c,r)	Supply price of composite (Armington) commodity c
PQD(c,r)	Consumer price of composite commodity c
PXC(c,r)	Producer price of composite domestic output

2. Production Block

2.1. General

PX(a,r)	Composite price of output by activity a
PVA(a,r)	Value added price for activity a in r
PINT(a,r)	Price of aggregate intermediate input
QX(a,r)	Domestic production by activity a in r
QVA(a,r)	Quantity of value added
QXC(c,r)	Domestic production by commodity c in r
QINT(a,r)	Aggregate quantity of intermediates used by activity a in r
QINTD(c,r)	Demand for (non-energy) intermediate inputs by commodity in r
ADVA(a,r)	TFP parameter for CES production functions for QVA
ADVASHFT(a,r)	TFP shifter
ADFD(f,a,r)	Factor and activity specific efficiency parameter
ADFDSHFT(f,r)	ADFD shifter
ADX(a,r)	QX production scale parameter when QVA and QINT are substitutes
WF(f,r)	Price of factor f in r
WFDIST(f,a,r)	Sectoral proportion for activity-specific factor prices in r
FD(f,a,r)	Demand for factor f by activity a in r
FS(f,r)	Supply of factor f in r

2.2 Energy

QVAE(a,r)	Value-added energy composite
QENE(a,r)	Composite energy demand by activity a
QFF(a,r)	Composie fossil fuel demand by activity a
QFFC(c,a,r)	Fossil fuel demand of type c by activity a
QELE(a,r)	Electricity demand by activity a
PVAE(a,r)	Price of value-added-energy composite
PENE(a,r)	Composite energy price in intermediate demand
PFF(a,r)	Composite fossil fuel price in intermediate demand

3. Household Block

YF(f,r)	Income to factor f
YFDIST(f,r)	Factor income for distribution after depreciation
YH(h,r)	Income to household h
HEXP(h,r)	Household consumption expenditure
QCD(c,h,r)	Household consumption by commodity c

4. Government Block

MTAX(r)	Import tariff revenue
ETAX(r)	Export tax revenue
STAX(r)	Sales tax revenue
ITAX(r)	Indirect production tax revenue
FYTAX(r)	Factor income tax revenue
HTAX(r)	Household income tax revenue

FTAX(r)	Factor use tax revenue
TEADJ(r)	Export subsidy scaling factor
TMADJ(r)	Tariff rate scaling factor
TSADJ(r)	Sales tax rate scaling factor
TXADJ(r)	Indirect production tax scaling factor
TYFADJ(r)	Factor income tax scaling factor
TYHADJ(r)	Income tax scaling factor
TFADJ(r)	Factor use tax scaling factor
DTE(r)	Uniform adjustment to export tax rates
DTM(r)	Uniform adjustment to tariff rates
DTS(r)	Uniform adjustment to sales tax rates
DTX(r)	Uniform adjustment to indirect production tax rates
DTYF(r)	Uniform adjustment to direct tax rates on factors
DTYH(r)	Uniform adjustment to direct tax rates on households
DTF(r)	Uniform adjustment to factor use tax rates
TE(c,w,r)	Export taxes on exports of c from r to w
TM(w,c,r)	Tariff rates on imports of c from w by r
TS(c,r)	Sales tax rate
TX(a,r)	Indirect production tax rate
TYF(f,r)	Direct tax rate on factor income
TYH(h,r)	Direct tax rate on households
TF(f,a,r)	Tax rate on factor use
YG(r)	Government income
QGD(c,r)	Government consumption demand by commodity c
QGDADJ(r)	Government consumption demand scaling factor
EG(r)	Total government consumption

5. Macro Closure Block

SHH(h,r)	Household saving rate s
SADJ(r)	Saving rate scaling factor
DSHH(r)	Partial household saving rate scaling factor
TOTSAV(r)	Total savings
QINVD(c,r)	Investment demand by commodity c
INVEST(r)	Total investment expenditure
IADJ(r)	Investment scaling factor
KAPGOV(r)	Government Savings
KAPWOR(r)	Current account balance
KAPREG(w,r)	Bilateral current account balance
VFDOMD(r)	Nominal Absorption
INVESTSH(r)	Value share of investment in total absorption
VGDSH(r)	Value share of government consumption in total absorption
RGDP(r)	Real GDP at factor cost
CPI(r)	Consumer price index - Region numeraires
PPI(r)	Producer (domestic) price index - Region numeraires
ERPI	Exchange rate index - Global numeraire

6. System Consistency Check

WALRAS(r)	Slack variable for S-I balance
KAPWORSYS	Slack variable for global balance of payments
GLOBESLACK	Slack variable for global trade margin service balance

A.1.3. Parameters

at(c,r)	Shift parameter for top-level CET function
gamma(c,r)	Share parameter for top-level CET function
rhot(c,r)	Substitution parameter for top-level CET function
atr(c,r)	Shift parameter for bottom-level CET function
gammar(c,r)	Share parameter for bottom-level CET function
rhoe(c,r)	Substitution parameter for bottom-level CET function
ac(c,r)	Shift parameter for Armington CES function
delta(c,r)	Share parameter for Armington CES function
rhoc(c,r)	Substitution parameter for Armington CES function
acr(c,r)	Shift parameter for Armington CES function over imports
deltar(w,c,r)	Share parameter for Armington CES function over imports
rhom(c,r)	Substitution parameter for Armington CES over imports
ioqmlqm(c,r)	Share of QML in QM
ioqmrqms(w,c,r)	Share of QMR in QMS
ioqmsqm(c,r)	Share of QMS in QM
margcor(w,c,cp,r)	Margin c per unit of r's import of commodity cp from region w
ntb(w,c,r)	Rate of iceberg transport costs
adxb(a,r)	Base Shift parameter for CES production functions for QX
deltax(a,r)	Share parameter for CES production functions for QX in r
rhox(a,r)	Substitution parameter for CES production function for QX in r
thetax(a,r)	Share of QVA in QX
ioqintqx(a,r)	Aggregate intermediate input quantity per unit of QX
ioqvaqx(a,r)	Value added per unit of QX
advab(a,r)	Base shift parameter for CES production functions for QVA
deltava(f,a,r)	Share parameters for CES production functions for QVA
rhova(a,r)	Substitution parameter for CES production function for QVA
adfdb(f,a,r)	Base shift parameter for factor and activity specific efficiency
ioqint(c,a,r)	Intermediate input output coefficients
ioqxcqx(a,c,r)	Share of commodity c in output by activity a
comtotsh(c,r)	Share of commodity c in total consumer demand
vddtotsh(c,r)	Share of value of domestic output for the domestic market
tradtotsh(ref)	Share of total exports by reference regions
deprec(f,r)	Depreciation rate by factor f on stock of factor f
hvash(h,f,r)	Share of income from factor f to household h
beta(c,h,r)	Marginal budget shares in consumption
qcdconst(c,h,r)	Volume of subsistence consumption
teb(c,w,r)	Base export tax rates on exports of c to region w
tmb(w,c,r)	Base tariff rates on imports from region w
tsb(c,r)	Base sales tax rate
txb(a,r)	Base indirect production tax rate on activity a
tyfb(f,r)	Base factor income tax rate
tyhb(h,r)	Base direct tax rate on household h
tfb(f,a,r)	Base factor use tax rate
dabte(c,w,r)	Change in base export tax rate

dabtm(w,c,r)	Change in base tariff rate
dabts(c,r)	Change in base sales tax rate
dabtx(a,r)	Change in base indirect tax rate
dabtyf(f,r)	Change in base direct tax rate on factors
dabtyh(h,r)	Change in base direct tax rate on households
dabtf(f,a,r)	Change in base factor use tax rate

te01(c,w,r)	0-1 par for potential flexing of export taxes
tm01(w,c,r)	0-1 par for potential flexing of tariff rates
ts01(c,r)	0-1 par for potential flexing of sales tax rates
tx01(a,r)	0-1 par for potential flexing of indirect production tax rates
tyf01(f,r)	0-1 par for potential flexing of direct tax rates on factors
tyh01(h,r)	0-1 par for potential flexing of direct tax rates on households
tf01(f,a,r)	0-1 par for potential flexing of factor use tax rates

qgdconst(c,r)	Government demand volume
qds(c,r)	Stock demand for commodity c

A.1.4. GAMS Equation Identifiers

1. Trade Block
1.1 Exports

PEDEF(c,r)	Composite export price for commodity c of origin r
PERDEF2(c,w,r)	Domestic price of exports of commodity c of origin r to region w
CET(c,r)	Upper-level CET function: QXC = CET(QE,QDS)
PXCDEF(c,r)	Producer price for composite domestic output
ESUPPLY(c,r)	Export supply function (FOC)
CETLEV2(c,w,r)	Export supply of c of origin r to region w (FOC)
CETALT(c,r)	QXC for commodities not exported by r or only produced for exports by r

1.2. Trade and Transport Margins

TSHIP(c,r)	Trade margin service exports by globe equal its trade margin imports
CETREQG(c,r)	Aggregate margin exports by globe
PERDEFHG(c,w,r)	Trade margin service export price
QTEQ	Total ct2 margin quantity on overall imports by r of origin w
GLOBEQUIL(c,r)	Region r's margin demand from globe equals globe's supply to r
PTDEF(c,r)	Price of trade margin commodity
KAPREQUIL2	Region r’s net margin service imports from globe

1.3. Imports

ARMINGTON(c,r)	Upper-Level Armington aggregator
COSTMIN(c,r)	Optimal import ratio (FOC)
PQSDEF(c,r)	Supply price of Armington composite
PQDDEF(c,r)	User price of Armington composite
ARMLEV2(w,c,r)	Import demand for c by r of origin w, where w’s share is large
PMDEF(c,r)	Aggregate price of imports of c by r
PMLDEF(c,r)	Aggregate price of imports of c with large share in r’s total imports of c
QMREQ(w,c,r)	Import demand for c by r of origin w, where w’s share is small
QMLEQ(c,r)	Total large-share imports of c by r
QMSEQ(c,r)	Total small-share imports of c by r
PMSDEF(c,r)	Aggregate price of imports of c with small share in r’s total imports of c
PWMDEF(w,c,r)	CIF price of imports of c by r of origin w
PMRDEF2(w,c,r)	Domestic tariff-inclusive price of imports of c by r of origin w
TRCONP(w,c,r)	FOB import price equals PWE plus iceberg ntb wedge
TRCONQ(w,c,r)	QMR – QER correspondence in presence of iceberg transport cost
ARMALT(c,r)	QQ for commodities not imported or not produced by r

2. Production Block
2.1. General

QVADEF(a,r)	Real value added (Leontief technology option)
QXPRODFN(a,r)	QX production function when VA and QINT are substitutes
QXFOC(a,r)	FOC for production function for QX of a in r level 1
PXDEF(a,r)	Composite price of output by activity a in region r
PVADEF(a,r)	Value added price determination
PINTDEF(a,r)	Price of intermediate input composite used by activity a
QVAPRODFN(a,r)	Value-added production function
QVAFOC(f,a,r)	Optimal factor demand
COMOUT(c,r)	Activity-commodity output correspondence
ADXEQ(a,r)	Scale parameter of QX production function when VA and QINT are substitutes
ADVAEQ(a,r)	Total factor productivity parameter
ADFDEQ(f,a,r)	Factor-augmenting productivity parameter
ADFDCALEQ(l,r)	Active only in dynamic labor productivity calibration mode
PXWEQ(a,r)	Activity output price in units of the global numeraire
QINTDEF(a,r)	Demand for composite intermediate input (Leontief technology option)
QVADEF(a,r)	Real value added (Leontief technology option)
QXPRODFN(a,r)	QX production function when VA and QINT are substitutes
QXFOC(a,r)	FOC for production function for QX of a in r level 1
PXDEF(a,r)	Composite price of output by activity a in region r
PVADEF(a,r)	Value added price determination
PINTDEF(a,r)	Price of intermediate input composite used by activity a
QVAPRODFN(a,r)	Value-added production function
QVAFOC(f,a,r)	Optimal factor demand
COMOUT(c,r)	Activity-commodity output correspondence
ADXEQ(a,r)	Scale parameter of QX production function when VA and QINT are substitutes
ADVAEQ(a,r)	Total factor productivity parameter
ADFDEQ(f,a,r)	Factor-augmenting productivity parameter

2.2. Energy

QVAEPRDFN1(a,r)	VA Energy nest
QVAEPRDFN2(a,r)	
PINTDEF1(a,r)	Price of non-energy intermediate input composite used by activity a
PINTDEF2(a,r)	Price of intermediate input composite used by activity a without energy nesting
QENEPRDFN(a,r)	Fossil Fuel Electricity nest
QFFPRDFN(a,r)	Coal Petrol Gas nest
QVAEEQ(a,r)	QVA QENE split
QENEEQ(a,r)	QELE QFF split
QFFCEQ(c,a,r)	QFFC split
PVAEEQ1(a,r)	Price of value added - energy composite
PVAEEQ2(a,r)	
PENEEQ(a,r)	Price of energy composite
PFFEQ(a,r)	Price of fossil fuel composite
QINTDEQ1(c,r)	Non-energy Intermediate input demand by commodity in region r
QINTDEQ2(c,r)	Fossil fuel intermediate input demand
QINTDEQ3(c,r)	Electricity intermediate input demand
QFFLEON(a,r)	Leontief specification for QENE nest for eneflag zero
QELELEON(a,r)	Leontief specification for QENE nest for eneflag zero

3. Household Block

YFEQ(f,r)	Gross factor income
YFDISTEQ(f,r)	Net factor income
YHEQ(h,r)	Household income
HEXPEQ(h,r)	Aggregate household expenditure
QCDEQ(c,h,r)	Household consumption by commodity

4. Government Block

4.1. Tax Revenue

MTAXEQ(r)	Import tariff revenue
ETAXEQ(r)	Export tax revenue
STAXEQ(r)	Sales tax Revenue
ITAXEQ(r)	Production tax revenue net of production subsidies
FYTAXEQ(r)	Factor income tax revenue
HTAXEQ(r)	Household income tax revenue
FTAXEQ(r)	Factor use tax revenue
YGEQ(r)	Total government revenue

4.2. Tax Rates

TEDEF(c,w,r)	Export tax rate
TMDEF(w,c,r)	Import tariff rate
TSDEF(c,r)	Sales tax rate
TXDEF(a,r)	Production tax-subsidy rate
TYFDEF(f,r)	Factor-specific factor income tax rates
TYHDEF(h,r)	Household income tax rate
TFDEF(f,a,r)	Factor use tax rate

4.3. Government Expenditure

EGEQ(r)	Total government consumption
QGDEQ(c,r)	Government consumption by commodity

5. Market Clearing Block

QEQUIL(c,r)	Commodity market equilibrium for Armington composite
FMEQUIL(f,r)	Factor market equilibrium
FSEQ(f,r)	Factor supply for non-activity-specific factors
SPECFACEQ(f,a,r)	Factor supply for activity-specific factors (natural resources)

6. Macro Closure Block

QINVDEQ(c,r)	Investment demand in by commodity
INVESTEQ(r)	Aggregate investment
TOTSAVEQ(r)	Total saving
SHHDEF(h,r)	Household propensity to save
KAPGOVEQ(r)	Government saving
KAPEQUIL(r)	Region r's current account deficit (foreign saving)
KAPREQUIL(w,r)	Region r's current account deficit with w (for non-globe regions)
VFDOMDEQ(r)	Nominal absorption
INVESTSHEQ(r)	Investment share in absorption
VGDSHEQ(r)	Government share in absorption
CPIDEF(r)	Consumer price index (Region numeraire)
PPIDEF(r)	Producer (domestic) price index (Region numeraire)
ERPIDEF	Exchange rate index (Global numeraire)

7. System Consistency Checks

COMTRADE(c,r)	Commodity trade balance for globe transactions
WALRASEQ(r)	Savings and Investment equilibrium
SYSEQUIL	System constraint on global balance of payments

.

A.2. The Algebra of GLOBE

1. Trade Block
1.1. Exports

PEDEF Composite export price for commodity c of origin r

$$PE_{c,r} = \sum_{w} \left(PER_{c,w,r} * QER_{c,w,r}\right) / QE_{c,r} \ , \qquad c \in ce, \quad r \in rgn$$

PERDEF2 Domestic price of exports of commodity c of origin r to region w

$$PER_{c,w,r} = PWE_{c,w,r} * \left(1 - TE_{c,w,r}\right) * ER_{r} \ , \qquad c \in cer$$

CET Upper-level CET function (QXC = CET(QE,QD)

$$QXC_{c,r} = at_{c,r} * \left(\gamma_{c,r} * \left(QE_{c,r}\right)^{\rho^{t}_{c,r}} + \left(1 - \gamma_{c,r}\right) * \left(QD_{c,r}\right)^{\rho^{t}_{c,r}}\right)^{1/\rho^{t}_{c,r}}$$

$$c \in (cd \cap ce), \quad r \in rgn$$

PXCDEF Price of composite output

$$PXC_{c,r} * QXC_{c,r} = \left(PD_{c,r} * QD_{c,r}\right) + \left(PE_{c,r} * QE_{c,r}\right) \ , \qquad c \in cx, r \in rgn$$

ESUPPLY Export supply (FOC)

$$QE_{c,r} = QD_{c,r} * \left(\left(PE_{c,r} / PD_{c,r}\right) * \left(\left(1 - \gamma_{c,r}\right) / \gamma_{c,r}\right)\right)^{1/(\rho^{t}_{c,r} - 1)}$$

$$c \in (cd \cap ce), \quad r \in rgn$$

CETLEV2 Export supply of c of origin r to region w (FOC)

$$QER_{c,w,r} = QE_{c,r} * \left(PER_{c,w,r} / \left(PE_{c,r} * \gamma^{r}_{c,w,r} * \left(atr_{c,r}\right)^{\rho^{e}_{c,r}}\right)\right)^{1/(\rho^{e}_{c,r} - 1)}$$

$$c \in cer, r \in rgn$$

NB:The elasticity of transformation between exports to different destinations is $\tau^{e}_{c,r} = 1/\left(\rho^{e}_{c,r} - 1\right)$.

CETALT QXC for commodities not exported by r or only produced for exports by r

$$QXC_{c,r} = QD_{c,r} + QE_{c,r} \ , \qquad c \in (cd \cap cen) \cup (cdn \cap ce), \ r \in rgn$$

1.2. Trade and Transport Margins

TSHIP Trade margin service exports by globe equal its trade margin imports

$QE_{ct2,globe} = QM_{ct2,globe}$

CETREQG Aggregate margin exports by globe

$QE_{ct2,globe} = \sum_{w} QER_{ct2,w,globe}$

PERDEFHG Trade margin service export price

$PER_{ct2,w,globe} = PE_{ct2,globe}$

QTEQ Total ct2 margin quantity on overall imports by r of origin w

$QT_{w,ct2,rgn} = \sum_{c} margcor_{w,ct2,c,rgn} QMR_{w,c,rgn}$

GLOBEQUIL Region r's margin demand from globe equals globe's supply to r

$\sum_{w} QT_{w,ct2,rgn} = QER_{ct2,rgn,globe}$

PTDEF Price of trade margin commodity

$PT_{ct2,rgn} = PWE_{ct2,rgn,globe}$

KAPREQUIL2 Region r's net margin service imports from globe

$KAPREG_{globe,r} = \sum_{ct2} \sum_{w} PT_{ct2,r} QT_{w,ct2,r} - \sum_{ct2} PWE_{ct2,globe,r} QER_{ct2,globe,r}$

1.3 Imports

ARMINGTON Upper-Level Armington aggregator

$$QQ_{c,r} = ac_{c,r} * \left(\delta_{c,r} * \left(QM_{c,r}\right)^{-\rho^{c}_{c,r}} + \left(1 - \delta_{c,r}\right) * \left(QD_{c,r}\right)^{-\rho^{c}_{c,r}}\right)^{-1/\rho^{c}_{c,r}}$$

$c \in (cx \cap cm), r \in rgn$

N.B: The elasticity of substitution between composite imports and the domestic substitute (Armington elasticity) is $\sigma^{c}_{c,r} = 1/(1 + \rho^{c}_{c,r})$.

COSTMIN Optimal import ratio (FOC)

$$QM_{c,r} = QD_{c,r} * \left(\left(PD_{c,r}/PM_{c,r}\right) * \left(\delta_{c,r}/\left(1 - \delta_{c,r}\right)\right)\right)^{1/(1+\rho^{c}_{c,r})}$$

$c \in (cx \cap cm), r \in rgn$

PQSDEF Supply price of Armington composite

$$PQS_{c,r} * QQ_{c,r} = \left(PD_{c,r} * QD_{c,r}\right) + \left(PM_{c,r} * QM_{c,r}\right), \qquad c \in (cd \cup cm), r \in rgn$$

PQDDEF User price of Armington composite

$$PQD_{c,r} = PQS_{c,r} * \left(1 + TS_{c,r}\right), \qquad c \in (cd \cup cm), r \in rgn$$

ARMLEV2 Import demand for c by r of origin w

$$QMR_{w,c,r} = QML_{c,r} * \left(\left(PMR_{w,c,r} * \left(acr_{c,r}\right)^{\rho_{c,r}^{m}} / PML_{c,r} * \delta_{w,c,r}^{r}\right)\right)^{-1/1+\rho_{c,r}^{m}}, \qquad c \in cmrl$$

NB:The elasticity of substitution between imports from different origins is $\sigma_{c,r}^{m} = 1/(1+\rho_{c,r}^{m})$.

PMDEF Composite price of imports of c by region r

$$PM_{c,r} * QM_{c,r} = \left(PML_{c,r} * QML_{c,r}\right) + \left(PMS_{c,r} * QMS_{c,r}\right), \qquad c \in cm$$

PMLDEF Composite price of large-share imports of c by region r

$$PML_{c,r} = \sum_{w \in cmrl(w,c,r)} \left(PMR_{w,c,r} * QMR_{w,c,r}\right) / QML_{c,r}, \qquad c \in cml(c,r)$$

NB: The summation is over origin regions with a market share > *smimpsh* in region r's total import bill for commodity c . Here *smimpsh* is a user-defined cut-off point to separate large and small share import flows.

QMLEQ Total large-share imports of c by r

$$QML_{c,r} = ioqmlqm_{c,r} * QM_{c,r}, \qquad c \in cml$$

QMSEQ Total small-share imports of c by r

$$QMS_{c,r} = ioqmsqm_{c,r} * QM_{c,r}, \qquad c \in cms$$

QMREQ Demand for imports with a tiny share in r's total imports of c

$$QMR_{w,c,r} = ioqmrqms_{w,c,r} * QMS_{c,r}, \qquad c \in cmrs(w,c,r)$$

PMSDEF Aggregate price of imports with a tiny share in r's total imports of c

$$PMS_{c,r} = \sum_{w} ioqmrqms_{w,c,r} * PMR_{w,c,r}, \qquad c \in cms(c,r)$$

PWMDEF CIF price of imports by r of origin w

$$PWM_{w,c,r} = PWMFOB_{w,c,r} + \sum_{cp \in ct2} margcor_{w,cp,c,r} * PT_{cp,r} \ , \qquad c \in cmr(w,c,r)$$

PMRDEF2 Domestic price of imports by r of origin w

$$PMR_{w,c,r} = PWM_{w,c,r} \cdot \left(1 + TM_{w,c,r}\right) \cdot ER_r \quad , \qquad c \in cmr(\text{w,c,r})$$

TRCONP PWMFOB equals PWE plus iceberg ntb wedge

$$PWMFOB_{w,c,r} = PWE_{c,w,r} \cdot \left(1 + ntb_{w,c,r}\right) \ , \qquad c \in cmr$$

TRCONQ QMR – QER correspondence in presence of iceberg transport cost

$$QMR_{w,c,r} \cdot \left(1 + ntb_{w,c,r}\right) = QER_{c,w,r} \quad , \qquad c \in cmr$$

ARMALT QQ for commodities not imported or not produced by r

$$QQ_{c,r} = QD_{c,r} + QM_{c,r} \quad , \qquad c \in (cx \cap cmn) \cup (cxn \cap cm)$$

2. Production Block
2.1. General

QINTDEF Demand for composite intermediate input (Leontief technology case)

$$QINT_{a,r} = ioqintqx_{a,r} * QX_{a,r} \qquad a \in aqxn, r \in rgn$$

QVADEF Real value added (Leontief technology case)

$$QVA_{a,r} = ioqvaqx_{a,r} * QX_{a,r} \qquad a \in aqxn, r \in rgn$$

QXPRODFN Gross output production function when VA and QINT are substitutes

$$QX_{a,r} = ADX_{a,r} \left(\left(\delta^x_{a,r} * QVA_{a,r}\right)^{-\rho^x_{a,r}} + \left(\left(1 - \delta^x_{a,r}\right) * QINT_{a,r}\right)^{-\rho^x_{a,r}} \right)^{-1/\rho^x_{a,r}}$$

$$a \in aqx, r \in rgn$$

QXFOC Optimal QVA-QINT ratio when VA and QINT are substitutes

$$QVA_{a,r} = QINT_{a,r} * \left(PINT_{a,r}/PVA_{a,r}\right) * \left(\delta^x_{a,r} / \left(1 - \delta^x_{a,r}\right)\right)^{1/\left(1+\rho^x_{a,r}\right)}$$

$$a \in aqx, r \in rgn$$

NB: The elasticity of substitution between value added and the composite intermediate input is $\sigma^x_{a,r} = 1/\left(1 + \rho^x_{a,r}\right)$.

PINTDEF Price of intermediate input composite

$$PINT_{a,r} = \sum_{c} \left(ioqint_{c,a,r} * PQD_{c,r} \right) \quad , \qquad r \in rgn$$

QINTDEQ Total intermediate input demand for commodity c

$$QINTD_{c,r} = \sum_{a} ioqint_{c,a,r} * QINT_{a,r} \quad , \qquad c \in cintd, r \in rgn$$

QVAPRODFN Value-added production function

$$QVA_{a,r} = ADVA_{a,r} * \left(\sum_{f} \delta_{f,a,r}^{va} * \left(ADFD_{f,a,r} * FD_{f,a,r} \right)^{-\rho_{a,r}^{va}} \right)^{-1/\rho_{a,r}^{va}} \quad , \qquad r \in rgn$$

NB: The elasticity of substitution between production factors is $\sigma_{a,r}^{va} = 1/\left(1 + \rho_{a,r}^{va}\right)$.

QVAFOC Optimal factor demand

$$WF_{f,r} * WFDIST_{f,a,r} * \left(1 + TF_{f,a,r}\right) = \frac{PVA_{a,r} * QVA_{a,r} * \left(\delta_{f,a,r}^{va} * ADFD_{f,a,r} \right)^{-\rho_{a,r}^{va}} * \left(FD_{f,a,r} \right)^{-\rho_{a,r}^{va}-1}}{\sum_{fp} \delta_{fp,a,r}^{va} * \left(ADFD_{f,a,r} * FD_{fp,a,r} \right)^{-\rho_{a,r}^{va}}} \qquad r \in rgn$$

PVADEF Value added price determination

$$PX_{a,r} * \left(1 - TX_{a,r}\right) * QX_{a,r} = \left(PVA_{a,r} * QVA_{a,r} \right) + \left(PINT_{a,r} * QINT_{a,r} \right), r \in rgn$$

PXDEF Composite price of output by activity in region r

$$PX_{a,r} = \sum_{c} ioqxcqx_{a,c,r} * PXC_{c,r} \quad , \qquad r \in rgn$$

COMOUT Activity – commodity output correspondence

$$QXC_{c,r} = \sum_{a} ioqxcqx_{a,c,r} * QX_{a,r} \quad , \qquad r \in rgn$$

ADVAEQ Total factor productivity

$$ADVA_{a,r} = advab_{a,r} ADVASHFT_{a,r} \quad , \qquad a \in acx, r \in rgn$$

ADFDEQ Factor-augmenting technical progress

$$ADFD_{f,a,r} = adfdb_{f,a,r} ADFDSHFT_{f,r} \quad , \qquad a \in acx, r \in rgn$$

ADXEQ

$$ADX_{a,r} = adxb_{a,r} \quad , \qquad a \in aqx\ , r \in rgn$$

2.2. Energy

QVAEPRDFN1 Production function for value-added-energy composite

$$QVAE_{a,r} = zvae_{a,r}\left(dva_{a,r} QVA_{a,r}^{-\rho vae_a} + dene_{a,r} QENE_{a,r}^{-\rho vae_a}\right)^{-\frac{1}{\rho vae_a}} \ , \qquad a \in aene, r \in rgn$$

QVAEPRDFN2 Dummy QVAE for activities without KLEM technology

$$QVAE_{a,r} = QVA_{a,r} \quad , \qquad a \neg\in aene\ , \quad r \in rgn$$

QENEPRDFN Energy composite

$$QENE_{a,r} = zene_{a,r}\left(dele_{a,r} QELE_{a,r}^{-\rho ene_a} + dff_{a,r} QFF_{a,r}^{-\rho ene_a}\right)^{-1/\rho ene_a} \ , a \in aene\ , r \in rgn$$

QFFPRDFN Fossil fuels composite

$$QFF_{a,r} = zff_{a,r} \prod_{cff} QFFC_{cff,a,r}^{dffc_{cff,a,r}} \quad , \qquad a \in aene\ , r \in rgn$$

QVAEEQ Optimal VA-energy ratio

$$QENE_{a,r} = \left(\frac{dene_{a,r}}{dva_{a,r}} \frac{PVA_{a,r}}{PENE_{a,r}}\right)^{1/(1+\rho vae_a)} QVA_{a,r} \quad , \qquad a \in aene\ , r \in rgn$$

QENEEQ Optimal ratio of electricity to direct fossil fuel use

$$QELE_{a,r} = \left(\frac{dff_{a,r}}{dele_{a,r}} \frac{PQD_{cele,r}}{PFF_{a,r}}\right)^{1/(1+\rho ene_a)} QFF_{a,r} \quad , \qquad a \in aene\ , r \in rgn$$

QFFCEQ Optimal fossil fuel use by type

$$QFFC_{cff,a,r} = \frac{dffc_{cff,a,r} PFF_{a,r} QFF_{a,r}}{PQD_{cff,r}} \quad , \qquad a \in aene\ , r \in rgn$$

PENEEQ Composite energy price

$$PENE_{a,r}QENE_{a,r} = PFF_{a,r}QFF_{a,r} + PQD_{cele,r}QELE_{a,r} \quad , \qquad a \in aene\ , r \in rgn$$

PVAEEQ1 Price of value-added-energy composite

$$PVAE_{a,r}QVAE_{a,r} = PVA_{a,r}QVA_{a,r} + PENE_{a,r}QENE_{a,r} \quad , \qquad a \in aene\ , r \in rgn$$

PVAEEQ2 Dummy PVAE for activities without KLEM technology

$$PVAE_{a,r} = PVA_{a,r} \quad , \qquad a \neg\in aene\ , r \in rgn$$

QFFLEON Intermediate demand for fossil fuel composite (Leontief option – eneflag = 0)

$$QFF_{a,r} = ioff_{a,r}QENE_{a,r} \quad , \qquad a \in aene\ , r \in rgn$$

QELELEON Intermediate demand for electricity (Leontief option – eneflag = 0)

$$QELE_{a,r} = ioele_{a,r}QENE_{a,r} \quad , \qquad a \in aene\ , r \in rgn$$

QINTDEQ1 Total non-energy intermediate input demand in r

$$QINTD_{cnener,r} = \sum_{a} ioqint_{cnener,a,r}\, QINT_{a,r} \quad , \qquad r \in rgn$$

QINTDEQ2 Total intermediate demand for fossil fuel type cff in r

$$QINTD_{cff,r} = \sum_{aene} QFFC_{cff,aene,r} + \sum_{a\neg\epsilon aene} ioqint_{cff,a,r}QINT_{a,r} \quad , \qquad r \in rgn$$

QINTDEQ3 Total intermediate electricity demand in r

$$QINTD_{cele,r} = \sum_{aene} QELE_{aene,r} + \sum_{a\neg\epsilon aene} ioqint_{cele,a,r}QINT_{a,r} \quad , \qquad r \in rgn$$

3. Household Block

YFEQ Gross factor income

$$YF_{f,r} = \sum_{a} WF_{f,r} * WFDIST_{f,a,r} * FD_{f,a,r} \quad , \qquad r \in rgn$$

YFDISTEQ Net factor income

$$YFDIST_{f,r} = \left(YF_{f,r} - \left(deprec_{f,r} * YF_{f,r}\right)\right) * \left(1 - TYF_{f,r}\right) \quad , \qquad r \in rgn$$

YHEQ Household income

$$YH_{h,r} = \sum_{f} hvash_{h,f,r} * YFDIST_{f,r}$$

$$+ \sum_{rp} (hhtrans_{r,rp} * \frac{ER_r}{ER_{rp}} - hhtrans_{rp,r}) \quad , \qquad r \in rgn$$

HEXPEQ Aggregate household expenditure

$$HEXP_{h,r} = YH_{h,r} * (1 - TYH_{h,r}) * (1 - SHH_{h,r}) \quad , \qquad r \in rgn$$

QCDEQ Household consumption demand by commodity

$$QCD_{c,h,r} *= \ qcdconst_{c,h,r} + \beta_{c,h,r} * (HEXP_{h,r} - \sum_c (qcdconst_{c,h,r} * PQD_{c,r})) / PQD_{c,r}$$

$$r \in rgn$$

4. Government Block

4.1. Tax Revenue

MTAXEQ Import tariff revenue

$$MTAX_r = \sum_{c,w} TM_{w,c,r} * PWM_{w,c,r} * ER_r * QMR_{w,c,r} \quad , \qquad r \in rgn$$

ETAXEQ Export tax revenue

$$ETAX_r = \sum_{c,w} TE_{c,w,r} * PWE_{c,w,r} * ER_r * QER_{c,w,r} \quad , \qquad r \in rgn$$

STAXEQ Sales tax revenue

$$STAX_r = \sum_{c} TS_{c,r} * PQS_{c,r} * \left(QINTD_{c,r} + \sum_{h} QCD_{c,h,r} + QGD_{c,r} + QINVD_{c,r} \right) ,$$

$$r \in rgn$$

ITAXEQ Indirect production tax revenue net of production subsidies

$$ITAX_r = \sum_{a} TX_{a,r} * PX_{a,r} * QX_{a,r} \quad , \qquad r \in rgn$$

FTAXEQ Factor use tax revenue

$$FTAX_r = \sum_{f,a} TF_{f,a,r} * WF_{f,r} * WFDIST_{f,ar} * FD_{f,a,r} \quad , \qquad r \in rgn$$

HTAXEQ Household income tax revenue

$$HTAX_r = \sum_h TYH_{h,r} * YH_{h,r} \quad , \qquad r \in rgn$$

FYTAXEQ Factor-specific factor income tax revenue

$$FYTAX_r = \sum_f TYF_{f,r} * \left(YF_{f,r} - \left(deprec_{f,r} * YF_{f,r}\right)\right) \quad , \qquad r \in rgn$$

YGEQ Total government revenue

$$YG_r = MTAX_r + ETAX_r + STAX_r + ITAX_r + FYTAX_r + HTAX_r + FTAX_r \qquad r \in rgn$$

4.2 Tax Rates

NB: The following equations for tax rates are specified to support model closures with fixed government savings and a proportional or additive endogenous shift in user-selected tax rates to match a fixed government savings volume. Consider TEDEF for example. The parameter cube teb contains the observed export tax rates in the benchmark year. In a standard closure with flexible government savings and fixed tax rates, $dabte_{c,w,r} = 0$, the multiplicative tax rate shift variable TEADJ is fixed at unity and the additive tax rate shift variable is fixed at zero. In a closure with fixed government savings and a proportional endogenous adjustment in TE, TEADJ would be flexed while maintaining $dabte_{c,w,r} = 0$. Non-proportional tax adjustments can be specified by chosing non-zero value for selected dabte entries. For uniform additive endogenous shifts in user-selected TE rates, the user would set the corresponding te01 entries to unity, flex DTE and fix TEADJ at unity while maintaining $dabte_{c,w,r} = 0$.

TEDEF Export tax rate

$$TE_{c,w,r} = \left(teb_{c,w,r} + dabte_{c,w,r}\right) * TEADJ_r + te01_{c,w,r} * DTE_r \quad , \qquad c \in cer$$

TMDEF Import tariff rate

$$TM_{w,c,r} = \left(tmb_{w,c,r} + dabtm_{w,c,r}\right) * TMADJ_r + tm01_{w,c,r} * DTM_r \quad , \qquad c \in cmr$$

TSDEF Sales tax rate

$$TS_{c,r} = \left(tsb_{c,r} + dabts_{c,r}\right) * TSADJ_r + ts01_{c,r} * DTS_r \quad , \qquad c \in (cd \cup cm)$$

TXDEF Production tax-subsidy rate

$$TX_{a,r} = \left(txb_{a,r} + dabtx_{a,r}\right) * TXADJ_r + tx01_{a,r} * DTX_r$$

TYFDEF Factor-specific factor income tax rate

$$TYF_{f,r} = \left(tyfb_{f,r} + dabtyf_{f,r}\right) * TYFADJ_r + tyf01_{a,r} * DTYF_r$$

TYHDEF Household income tax rate

$$TYH_{h,r} = \left(tyhb_{h,r} + dabtyh_{h,r}\right) * TYHADJ_r + tyh01_{h,r} * DTYH_r$$

TFDEF Factor use tax rate

$$TF_{f,a,r} = \left(tfb_{f,a,r} + dabtf_{f,a,r}\right) * TFADJ_r + tf01_{f,a,r} * DTF_r$$

4.3 Government Expenditure

EGEQ Total government consumption

$$EG_r = \sum_c QGD_{c,r} * PQD_{c,r} \quad , \qquad r \in rgn$$

QGDEQ Government consumption by commodity

$$QGD_{c,r} = qgdconst_{c,r} * QGDADJ_r \quad , \qquad r \in rgn$$

5. Market Clearing Block

QEQUIL Commodity market equilibrium for Armington composite

$$QQ_{c,r} = QINTD_{c,r} + \sum_h QCD_{c,h,r} + QGD_{c,r} + QINVD_{c,r} + qds_{c,r} \, ,$$

$$c \in (cd \cup cm), r \in rgn$$

FMEQUIL Factor market equilibrium

$$FS_{f,r} = \sum_a FD_{f,a,r} \quad , \qquad r \in rgn$$

FSEQ Factor supply for non-activity-specific factors

$$FS_{f,r} = FS0_{f,r} * \left(\frac{WF_{f,r}}{WF0_{f,r}}\right)^{fselas_{f,r}} \quad , \qquad f \in \neg spfac, r \in rgn$$

SPECFACEQ Factor supply for activity-specific factors (natural resources)

$$FD_{f,a,r} = FD0_{f,a,r} * \left(\frac{WF_{f,r} WFDIST_{f,a,r}}{WF0_{f,r} WFDIST0_{f,a,r}}\right)^{fdelas_{f,a,r}} \quad , \qquad f \in spfac,\ r \in rgn$$

6. Macro Closure Block

QINVDEQ Investment demand by commodity

$$QINVD_{c,r} = \sum_{c} qinvdconst_{c,r} * IADJ_r \quad , \qquad r \in rgn$$

INVESTEQ Aggregate investment demand

$$INVEST_r = \sum_{c} PQD_{c,r} * QINVD_{c,r} \quad , \qquad r \in rgn$$

TOTSAVEQ Total Saving

$$TOTSAV_r = \left(\sum_{h} \left(YH_{h,r} * \left(1 - TYH_{h,r}\right) * SHH_{h,r}\right)\right) + \left(\sum_{f} \left(deprec_{f,r} * YF_{f,r}\right)\right) + KAPGOV_r + \left(KAPWOR_r * ER_r\right) \ , \quad r \in rgn$$

SHHDEF Household propensity to save

$$SHH_{h,r} = shhb_{h,r} * SADJ_r \quad , \qquad r \in rgn$$

KAPGOVEQ Government saving

$$KAPGOV_r = YG_r - EG_r \quad , \qquad r \in rgn$$

KAPREGEQ Region r’s trade deficit with region w

$$KAPREG_{w,r} = \sum_{c} \left(PWMFOB_{w,c,r} * QMR_{w,c,r}\right) - \sum_{c} \left(PWE_{c,w,r} * QER_{c,w,r}\right) \ , \quad w \in wgn$$

KAPEQUIL Region r’s total current account deficit (Foreign saving)

$$KAPWOR_r = \sum_w KAPREG_{w,r} + \sum\nolimits_{rp} (hhtrans_{rp,r} - hhtrans_{r,rp})$$

VFDOMDEQ Nominal absorption

$$VFDOMD_r = \sum_c PQD_{c,r} * \left(\left(\sum_h QCD_{c,h,r} \right) + QGD_{c,r} + QINVD_{c,r} \right) \quad , \qquad r \in rgn$$

VGDSHEQ Government share in absorption

$$VGDSH_r * VFDOMD_r = \sum_c \left(PQD_{c,r} * QGD_{c,r} \right) \quad , \qquad r \in rgn$$

INVESTSHEQ Investment share in absorption

$$INVESTSH_r * VFDOMD_r = INVEST_r \quad , \qquad r \in rgn$$

CPIDEF Consumer price index

$$CPI_r = \sum_c \left(comtotsh_{c,r} * PQD_{c,r} \right) \quad , \qquad r \in rgn$$

PPIDEF Producer price index

$$PPI_r = \sum_c \left(vddtotsh_{c,r} * PD_{c,r} \right) \quad , \qquad r \in rgn$$

ERPIDEF

$$ERPI = \sum_{ref} \left(tradtotsh_r * ER_{ref} \right)$$

7. System Consistency Checks

COMTRADE Global margin service import value must match margin export value

$$\sum\nolimits_w PWM_{w,ct2,globe} QMR_{w,ct2,globe} = \sum\nolimits_w PWE_{ct2,w,globe} QER_{ct2,w,globe} + GLOBESLACK$$

WALRASEQ Total savings must match total investment including stock changes

$$TOTSAV_r = INVEST_r + \sum\nolimits_c PQD_{c,r} qds_{c,r} + WALRAS \quad , \qquad r \in rgn$$

SYSEQUIL Global sum of regional current account balances must be zero

$$KAPWORSYS = \sum_{rgn} KAPWOR_{rgn} \quad .$$

Appendix B: IMPACT-GTAP-GLOBE Concordances

B.1 Concordances

The GLOBE-Energy model is calibrated to the Global Trade Analysis Project (GTAP) database. This data set provides a detailed and internally consistent representation the global economy-wide structure of production, demand and international trade at a regionally and sectorally disaggregated level. GTAP 8.1 – the latest available version of the database at the start of the project - combines detailed bilateral trade and protection data reflecting economic linkages among 135 world regions with individual regional input-output data, which account for intersectoral linkages among 57 production sectors for the benchmark year 2007.

Table B1 displays the mapping from IMPACT cty regions to GTAP 8.1 regions, while Tables B2 and B3 report the concordances between GTAP agricultural and matched processed food commodities / sectors on the one hand, and IMPACT activities and IMPACT commodities respectively on the other. The concordances have been constructed by a careful inspection of the detailed GTAP classification where necessary.

Table B1: Concordance between IMPACT Regions and GTAP 8.1 Regions

IMPACT Name	IMPACT cty	GTAP 8.1 reg	GTAP Name	GLOBE-15 r
Afghanistan	AFG	xsa	Rest of South Asia	OSthAsia
Angola	AGO	xac	South Central Africa	EAfrica
Albania	ALB	alb	Albania	FSU
Argentina	ARG	arg	Argentina	SAmerica
Armenia	ARM	arm	Armenia	FSU
Australia	AUS	aus	Australia	Oceania
Austria	AUT	aut	Austria	EEA
Azerbaijan	AZE	aze	Azerbaijan	FSU
Burundi	BDI	xec	Rest of East Africa	EAfrica
Benin	BEN	ben	Benin	WAfrica
Burkina Faso	BFA	bfa	Burkina Faso	WAfrica
Bangladesh	BGD	bgd	Bangladesh	OSthAsia
Bulgaria	BGR	bgr	Bulgaria	EEA
Belarus	BLR	blr	Belarus	FSU
Baltic States	BLT	est	Estonia	EEA
Baltic States	BLT	ltu	Lithuania	EEA
Baltic States	BLT	lva	Latvia	EEA
Belgium-Luxembourg	BLX	bel	Belgium	EEA
Belgium-Luxembourg	BLX	lux	Luxembourg	EEA
Belize	BLZ	xca	Rest of Central America	CAmerica
Bolivia	BOL	bol	Bolivia	SAmerica
Brazil	BRA	bra	Brazil	SAmerica

IMPACT Name	IMPACT	GTAP 8.1	GTAP Name	GLOBE-15
Bhutan	BTN	xsa	Rest of South Asia	OSthAsia
Botswana	BWA	bwa	Botswana	SAfrica
Central African Republic	CAF	xcf	Central Africa	EAfrica
Canada	CAN	can	Canada	NAmerica
Chile	CHL	chl	Chile	SAmerica
China Plus	CHM	chn	China	China
Switzerland plus	CHP	che	Switzerland	EEA
Ivory Coast	CIV	civ	Ivory Coast	WAfrica
Cameroon	CMR	cmr	Cameroon	WAfrica
Democratic Republic of Congo	COD	xac	South Central Africa	EAfrica
Congo	COG	xcf	Central Africa	EAfrica
Colombia	COL	col	Colombia	SAmerica
Other Caribbean	CRB	xcb	Rest of Caribbean	CAmerica
Costa Rica	CRI	cri	Costa Rica	CAmerica
Cuba	CUB	xcb	Rest of Caribbean	CAmerica
Cyprus	CYP	cyp	Cyprus	EEA
Czech Republic	CZE	cze	Czech Republic	EEA
Germany	DEU	deu	Germany	EEA
Djibouti	DJI	xec	Rest of East Africa	EAfrica
Denmark	DNK	dnk	Denmark	EEA
Dominican Republic	DOM	xcb	Rest of Caribbean	CAmerica
Algeria	DZA	xnf	Rest of North Africa	MENA
Ecuador	ECU	ecu	Ecuador	SAmerica
Egypt	EGY	egy	Egypt	MENA
Eritrea	ERI	xec	Rest of East Africa	EAfrica
Ethiopia	ETH	eth	Ethiopia	EAfrica
Fiji	FJI	xoc	Rest of Oceania	Oceania
Finland Plus	FNP	fin	Finland	EEA
France plus	FRP	fra	France	EEA
Gabon	GAB	xcf	Gabon	EAfrica
Georgia	GEO	geo	Georgia	FSU
Ghana	GHA	gha	Ghana	WAfrica
Guinea	GIN	gin	Guinea	WAfrica
Gambia	GMB	xwf	Rest of West Africa	WAfrica
Guinea-Bissau	GNB	xwf	Rest of West Africa	WAfrica
Equatorial Guinea	GNQ	xcf	Rest of Central Africa	EAfrica
Greece	GRC	grc	Greece	EEA
Greenland	GRL	xna	Rest of North America	NAmerica
Guyanas South America	GSA	xsm	Rest of South America	SAmerica
Guatemala	GTM	gtm	Guatemala	CAmerica
Honduras	HND	hnd	Honduras	CAmerica
Croatia	HRV	hrv	Croatia	FSU
Haiti	HTI	xcb	Rest of Caribbean	CAmerica
Hungary	HUN	hun	Hungary	EEA
Indonesia	IDN	idn	Indonesia	OEastAsia
India	IND	ind	India	India

IMPACT Name	IMPACT	GTAP 8.1	GTAP Name	GLOBE-15
Ireland	IRL	irl	Ireland	EEA
Iran	IRN	irn	Iran	MENA
Iraq	IRQ	xws	Rest of West Asia	MENA
Iceland	ISL	xef	Iceland	EEA
Israel	ISR	isr	Israel	MENA
Italy plus	ITP	ita	Italy	EEA
Jamaica	JAM	xcb	Rest of Caribbean	CAmerica
Jordan	JOR	xws	Rest of West Asia	MENA
Japan	JPN	jpn	Japan	HIAsia
Kazakhstan	KAZ	kaz	Kazakhstan	FSU
Kenya	KEN	ken	Kenya	EAfrica
Kyrgyzstan	KGZ	kgz	Kyrgyzstan	FSU
Cambodia	KHM	khm	Cambodia	OEastAsia
South Korea	KOR	kor	South Korea	HIAsia
Laos	LAO	lao	Laos	OEastAsia
Lebanon	LBN	xws	Rest of West Asia	MENA
Liberia	LBR	xwf	Rest of West Africa	WAfrica
Libya	LBY	xnf	Rest of North Africa	MENA
Sri Lanka	LKA	lka	Sri Lanka	OSthAsia
Lesotho	LSO	xsc	Rest of SACU	SAfrica
Moldova	MDA	xee	Moldova	FSU
Madagascar	MDG	mdg	Madagascar	EAfrica
Mexico	MEX	mex	Mexico	CAmerica
Mali	MLI	xwf	Rest of West Africa	WAfrica
Mongolia	MNG	mng	Mongolia	FSU
Morocco	MOR	mar	Morocco	MENA
Mozambique	MOZ	moz	Mozambique	EAfrica
Mauritania	MRT	xwf	Rest of West Africa	WAfrica
Malawi	MWI	mwi	Malawi	EAfrica
Malaysia	MYS	mys	Malaysia	OEastAsia
Namibia	NAM	nam	Namibia	SAfrica
Niger	NER	xwf	Rest of West Africa	WAfrica
Nigeria	NGA	nga	Nigeria	WAfrica
Nicaragua	NIC	nic	Nicaragua	CAmerica
Netherlands	NLD	nld	Netherlands	EEA
Norway	NOR	nor	Norway	EEA
Nepal	NPL	npl	Nepal	OSthAsia
New Zealand	NZL	nzl	New Zealand	Oceania
Other Pacific Ocean	OPO	xoc	Rest of Oceania	Oceania
Other Southeast Asia	OSA	xse	Rest of Southeast Asia	OEastAsia
Pakistan	PAK	pak	Pakistan	OSthAsia
Panama	PAN	pan	Panama	CAmerica
Peru	PER	per	Peru	SAmerica
Philippines	PHL	phl	Philippines	OEastAsia
Papua New Guinea	PNG	xoc	Rest of Oceania	Oceania
Poland	POL	pol	Poland	EEA

IMPACT Name	IMPACT	GTAP 8.1	GTAP Name	GLOBE-15
North Korea	PRK	xea	Rest of East Asia	OEastAsia
Portugal	PRT	prt	Portugal	EEA
Paraguay	PRY	pry	Paraguay	SAmerica
Occupied Palestinian Territory	PSE	xws	Rest of West Asia	MENA
Rest of Arab Peninsula	RAP	are	United Arab Emirates	MENA
Romania	ROU	rou	Romania	FSU
Russia	RUS	rus	Russia	FSU
Rwanda	RWA	rwa	Rwanda	EAfrica
Saudi Arabia	SAU	sau	Saudi Arabia	MENA
Sudan	SDN	xec	Rest of East Africa	EAfrica
Senegal	SEN	sen	Senegal	WAfrica
Solomon Islands	SLB	xoc	Rest of Oceania	Oceania
Sierra Leone	SLE	xwf	Rest of West Africa	WAfrica
El Salvador	SLV	slv	El Salvador	CAmerica
Somalia	SOM	xec	Rest of East Africa	EAfrica
Spain plus	SPP	esp	Spain	EEA
South Sudan	SSD	xec	Rest of East Africa	EAfrica
Slovakia	SVK	svk	Slovakia	EEA
Slovenia	SVN	svn	Slovenia	EEA
Sweden	SWE	swe	Sweden	EEA
Swaziland	SWZ	xsc	Swaziland	SAfrica
Syria	SYR	xws	Rest of West Asia	MENA
Chad	TCD	xcf	Rest of Central Africa	EAfrica
Togo	TGO	tgo	Togo	WAfrica
Thailand	THA	tha	Thailand	OEastAsia
Tajikistan	TJK	xsu	Rest of Former SU	FSU
Turkmenistan	TKM	xsu	Rest of Former SU	FSU
Timor-L'este	TLS	xse	Rest of Southeast Asia	OEastAsia
Tunisia	TUN	tun	Tunisia	MENA
Turkey	TUR	tur	Turkey	MENA
Tanzania	TZA	tza	Tanzania	EAfrica
Uganda	UGA	uga	Uganda	EAfrica
Great Britain plus	UKP	gbr	Great Britain	EEA
Ukraine	UKR	ukr	Ukraine	FSU
Uruguay	URY	ury	Uruguay	SAmerica
United States	USA	usa	United States	NAmerica
Uzbekistan	UZB	xsu	Rest of Former SU	FSU
Venezuela	VEN	ven	Venezuela	SAmerica
Vietnam	VNM	vnm	Vietnam	OEastAsia
Vanuatu	VUT	xoc	Rest of Oceania	Oceania
Yemen	YEM	xws	Rest of West Asia	MENA
South Africa	ZAF	zaf	South Africa	SAfrica
Zambia	ZMB	zmb	Zambia	EAfrica
Zimbabwe	ZWE	zwe	Zimbabwe	EAfrica

Table B2: Concordance between IMPACT Activities and GTAP 8.1 Commodities

IMPACT Name	IMPACT jj	GTAP Name	GTAP com
Cattle	jbeef	Bovine cattle, sheep and goats, horses	ctl
Pigs	jpork	Animal products nec	oap
Sheep and Goats	jlamb	Bovine cattle, sheep and goats, horses	ctl
Poultry	jpoul	Animal products nec	oap
Eggs	jeggs	Animal products nec	oap
Dairy	jmilk	Raw milk	rmk
Barley	jbarl	Cereal grains nec	gro
Maize	jmaiz	Cereal grains nec	gro
Millet	jmill	Cereal grains nec	gro
Rice	jrice	Paddy rice	pdr
Sorghum	jsorg	Cereal grains nec	gro
Wheat	jwhea	Wheat	wht
Other Cereals	jocer	Cereal grains nec	gro
Cassava	jcass	Vegetables, fruit, nuts	v_f
Potato	jpota	Vegetables, fruit, nuts	v_f
Sweet Potatoes	jswpt	Vegetables, fruit, nuts	v_f
Yams	jyams	Vegetables, fruit, nuts	v_f
Other Roots & Tubers	jorat	Vegetables, fruit, nuts	v_f
Beans	jbean	Vegetables, fruit, nuts	v_f
Chickpeas	jchkp	Vegetables, fruit, nuts	v_f
Cowpeas	jcowp	Vegetables, fruit, nuts	v_f
Lentils	jlent	Vegetables, fruit, nuts	v_f
Pigeonpeas	jpigp	Vegetables, fruit, nuts	v_f
Other Pulses	jopul	Vegetables, fruit, nuts	v_f
Bananas	jbana	Vegetables, fruit, nuts	v_f
Plantains	jplnt	Vegetables, fruit, nuts	v_f
(Sub)-Tropical Fruits	jsubf	Vegetables, fruit, nuts	v_f
Temperate Fruits	jtemf	Vegetables, fruit, nuts	v_f
Vegetables	jvege	Vegetables, fruit, nuts	v_f
Sugarcane	jsugc	Sugar cane, sugar beet	c_b
Sugarbeet	jsugb	Sugar cane, sugar beet	c_b
Cane Sugar	jsugrc	Sugar	sgr
Beet Sugar	jsugrb	Sugar	sgr
Groundnuts	jgrnd	Oil seeds	osd
Groundnuts for Oil	jgdnt	Oil seeds	osd
Rapeseed	jrpsd	Oil seeds	osd
Rapeseed for Oil	jrpnt	Oil seeds	osd
Soybeans	jsoyb	Oil seeds	osd
Soybeans for Oil	jsbnt	Oil seeds	osd
Sunflower Seeds	jsnfl	Oil seeds	osd
Sunflower Seeds for Oil	jsfnt	Oil seeds	osd
Oil Palm Fruit	jpalm	Oil seeds	osd
Palm Oil	jplol	Vegetable oils and fats	vol

IMPACT Name	IMPACT	GTAP Name	GTAP
Palm Kernal	jpkrl	Vegetable oils and fats	vol
Palm Kernal Oil	jpkol	Vegetable oils and fats	vol
Total Other Oilseeds	jtols	Oil seeds	osd
Total Other Oilseeds for Oil	jtont	Oil seeds	osd
Groundnut oil from gdnt	jgdoln	Vegetable oils and fats	vol
Rapeseed oil from rpnt	jrpoln	Vegetable oils and fats	vol
Soybean Oil from sbnt	jsboln	Vegetable oils and fats	vol
Sunflower Oil from sfnt	jsfoln	Vegetable oils and fats	vol
Total Other oils from tont	jtooln	Vegetable oils and fats	vol
Groundnut oil from grnd	jgdolt	Vegetable oils and fats	vol
Rapeseed oil from rpsd	jrpolt	Vegetable oils and fats	vol
Soybean Oil from soyb	jsbolt	Vegetable oils and fats	vol
Sunflower Oil from snfl	jsfolt	Vegetable oils and fats	vol
Total other oils from tols	jtoolt	Vegetable oils and fats	vol
Cocoa	jcoco	Crops nec	ocr
Coffee	jcafe	Crops nec	ocr
Cotton	jcott	Plant-based fibres	pfb
Tea	jteas	Crops nec	ocr
Other Crops	jothr	Crops nec	ocr
Fodders	jfodr	Crops nec	ocr
Grass	jpstr	Crops nec	ocr

Table B3: Concordance between IMPACT and GTAP 8.1 Commodities

IMPACT Name	IMPACT cc	GTAP Name com	GTAP com
Cattle	cbeef	Bovine cattle, sheep and goats, horses	ctl
Pigs	cpork	Animal products nec	oap
Sheep and Goats	clamb	Bovine cattle, sheep and goats, horses	ctl
Poultry	cpoul	Animal products nec	oap
Eggs	ceggs	Animal products nec	oap
Dairy	cmilk	Raw milk	rmk
Barley	cbarl	Cereal grains nec	gro
Maize	cmaiz	Cereal grains nec	gro
Millet	cmill	Cereal grains nec	gro
Rice	crice	Paddy rice	pdr
Sorghum	csorg	Cereal grains nec	gro
Wheat	cwhea	Wheat	wht
Other Cereals	cocer	Cereal grains nec	gro
Cassava	ccass	Vegetables, fruit, nuts	v_f
Potato	cpota	Vegetables, fruit, nuts	v_f
Sweet Potatoes	cswpt	Vegetables, fruit, nuts	v_f
Yams	cyams	Vegetables, fruit, nuts	v_f
Other Roots & Tubers	corat	Vegetables, fruit, nuts	v_f
Beans	cbean	Vegetables, fruit, nuts	v_f

IMPACT Name	IMPACT	GTAP Name	GTAP
Chickpeas	cchkp	Vegetables, fruit, nuts	v_f
Cowpeas	ccowp	Vegetables, fruit, nuts	v_f
Lentils	clent	Vegetables, fruit, nuts	v_f
Pigeonpeas	cpigp	Vegetables, fruit, nuts	v_f
Other Pulses	copul	Vegetables, fruit, nuts	v_f
Bananas	cbana	Vegetables, fruit, nuts	v_f
Plantains	cplnt	Vegetables, fruit, nuts	v_f
(Sub)-Tropical Fruits	csubf	Vegetables, fruit, nuts	v_f
Temperate Fruits	ctemf	Vegetables, fruit, nuts	v_f
Vegetables	cvege	Vegetables, fruit, nuts	v_f
Sugarcane	csugc	Sugar cane, sugar beet	c_b
Sugarbeet	csugb	Sugar cane, sugar beet	c_b
Sugar	csugr	Sugar	sgr
Groundnuts	cgrnd	Oil seeds	osd
Groundnuts for Oil	cgdnt	Oil seeds	osd
Groundnut Oil	cgdol	Vegetable oils and fats	vol
Groundnut Meal	cgdml	Oil seeds	vol
Rapeseed	crpsd	Oil seeds	osd
Rapeseed for Oil	crpnt	Oil seeds	osd
Rapeseed Oil	crpol	Vegetable oils and fats	vol
Rapeseed Meal	crpml	Vegetable oils and fats	vol
Soybeans	csoyb	Oil seeds	osd
Soybeans for Oil	csbnt	Oil seeds	osd
Soybean Oil	csbol	Vegetable oils and fats	vol
Soybean Meal	csbml	Vegetable oils and fats	vol
Sunflower Seeds	csnfl	Oil seeds	osd
Sunflower Seeds for Oil	csfnt	Oil seeds	osd
Sunflower Oil	csfol	Vegetable oils and fats	vol
Sunflower Meal	csfml	Vegetable oils and fats	vol
Oil Palm Fruit	cpalm	Oil seeds	osd
Palm Oil	cplol	Vegetable oils and fats	vol
Palm Kernel	cpkrl	Vegetable oils and fats	vol
Palm Kernel Oil	cpkol	Vegetable oils and fats	vol
Palm Kernel Meal	cpkml	Vegetable oils and fats	vol
Total Other Oilseeds	ctols	Oil seeds	osd
Total Other Oilseeds for Oil	ctont	Oil seeds	osd
Total Other Oils	ctool	Vegetable oils and fats	vol
Total Other Oilseed Meal	ctoml	Vegetable oils and fats	vol
Cocoa	ccoco	Crops nec	ocr
Coffee	ccafe	Crops nec	ocr
Cotton	ccott	Plant-based fibres	pfb
Tea	cteas	Crops nec	ocr
Other Crops	cothr	Crops nec	ocr
Fodders	cfodr	Crops nec	ocr
Grass	cgrss	Crops nec	ocr

Table B4: Commodity Group Aggregation of the GTAP 8.1 Database

	Description	Code		Description	Code
1	Paddy rice	pdr	27	Textiles	tex
2	Wheat	wht	28	Wearing apparel	wap
3	Cereal grains nec	gro	29	Leather products	lea
4	Oil seeds	osd	30	Wood products	lum
5	Vegetable oils and fats	vol	31	Paper products, publishing	ppp
6	Sugar cane, sugar beet	c_b	32	Chemical,rubber,plastic products	crp
7	Vegetables, fruit, nuts	v_f	33	Petroleum, coal products	p_c
8	Plant-based fibers	pfb	34	Mineral products nec	nmm
9	Crops nec	ocr	35	Ferrous metals	i_s
10	Wool, silk-worm cocoons	wol	36	Metals nec	nfm
11	Cattle, sheep, goats, horses	ctl	37	Metal products	fmp
12	Animal products nec	oap	38	Motor vehicles and parts	mvh
13	Raw milk	rmk	39	Transport equipment nec	otn
14	Forestry	frs	40	Electronic equipment	ele
15	Fishing	fsh	41	Machinery and equipment nec	ome
16	Coal	coa	42	Manufactures nec	omf
17	Oil	oil	43	Electricity	ely
18	Gas	gas	44	Gas manufacture, distribution	gdt
19	Minerals nec	omn	45	Water	wtr
20	Processed rice	pcr	46	Construction	cns
21	Sugar	sgr	47	Trade	trd
22	Meat: cattle, sheep, goats horse	cmt	48	Transport nec	otp
23	Meat products nec	omt	49	Sea transport	wtp
24	Dairy products	mil	50	Air transport	atp
25	Food products nec	ofd	51	Communication	cmn
26	Beverages and tobacco products	b_t	52	Financial services nec	ofi
			53	Insurance	isr
			54	Business services nec	obs
			55	Recreation and other services	ros
			56	Public administration, defence, health, education	osg
			57	Dwellings	dwe

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